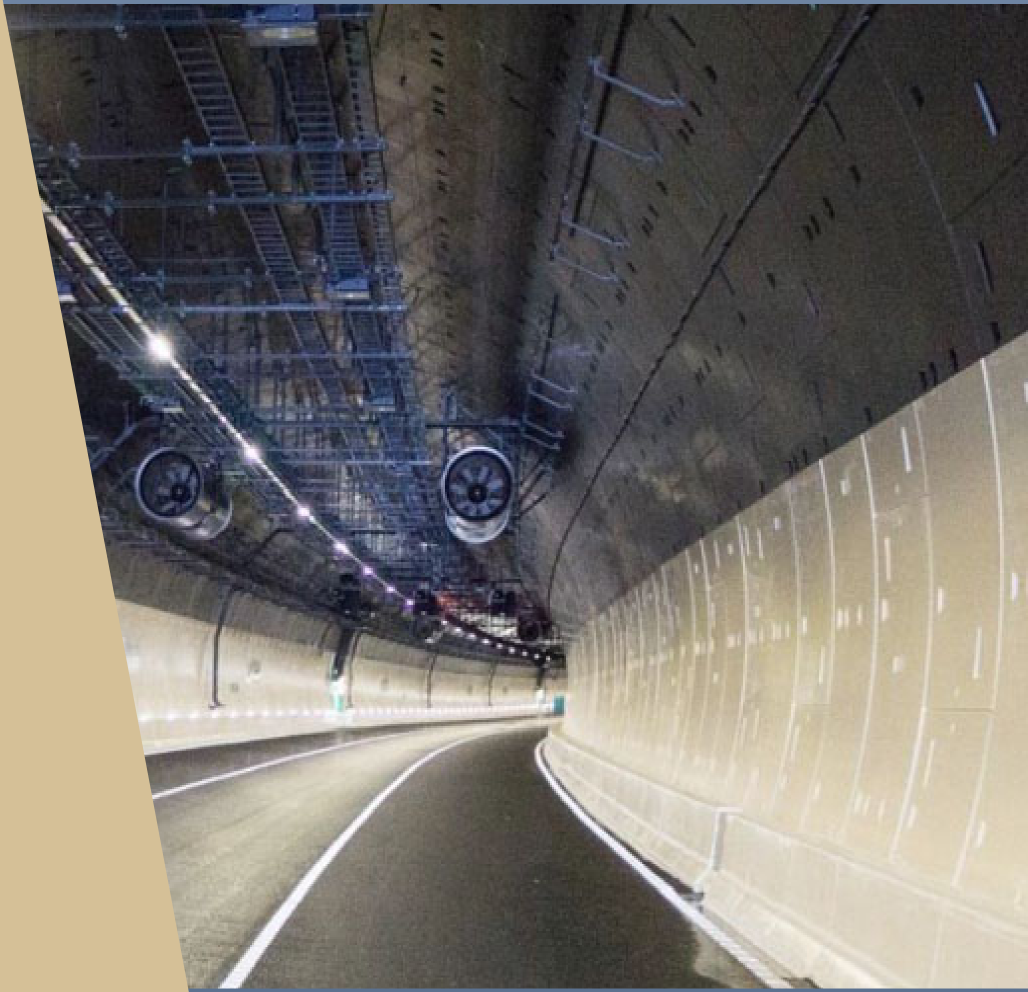
U.S. Department of Transportation
Federal Highway Administration

FIXED FIRE FIGHTING AND EMERGENCY VENTILATION SYSTEMS FOR HIGHWAY TUNNELS – LITERATURE SURVEY AND SYNTHESIS



FHWA-HIF-20-016

Technical Report Documentation Page

1. Report No.
FHWA-HIF-20-016

2. Government Accession No.
TBA

3. Recipient's Catalog No.
TBA

4. Title and Subtitle
Fixed Fire Fighting and Emergency Ventilation Systems
Literature Survey and Synthesis

5. Report Date
January 2020

6. Performing Organization Code
TBA

7. Principal Investigator(s):
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8. Performing Organization Report
TBA

9. Performing Organization Name and Address
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One Penn Plaza
250 West 34th Street
New York, NY, 10119

10. Work Unit No. (TRAIS)
TBA

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
TBA

14. Sponsoring Agency Code
TBA

15. Supplementary Notes

16. Abstract

There is a lot of global experience with fixed fire fighting systems in road tunnels, particularly in Australia and Japan, but also in several recently constructed tunnels in the United States and Europe. The U.S. first implemented FFFS in their tunnels in the 1950s, however, this approach did not become routine, partly due to unsuccessful tests of FFFS in the Offneg Tunnel in Europe. Because FFFS were not routinely applied in all tunnels, the present-day approach can vary between planned facilities and regions, especially in critical design areas such as operational integration with the emergency ventilation system (EVS). Recent testing, fire incidents, and modeling efforts have demonstrated that FFFS lessen the fire hazard by cooling combustion products and (in certain circumstances) suppressing the fire (reducing the fire heat release rate [FHRR]). Further research and a design-focused approach to computational modeling and testing is needed to develop a set of suggested practices on the integration of FFFS and the EVS. The end goal of the research is to facilitate design of the FFFS and EVS in an integrated manner.

17. Key Words
Fixed fire fighting system, FFFS, deluge, tunnel, tunnel ventilation

18. Distribution Statement
No restrictions.

19. Security Classif. (of this report)
UNCLASSIFIED

20. Security Classif. (of this page)
UNCLASSIFIED

21. No. of Pages
TBA

22. Price

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

ACRONYMS

Abbreviation	**Detail**
AASHTO	American Association of State Highway Transportation Officials
AFFF	Aqueous Film Forming Foam
AHJ	Authority Having Jurisdiction
AID	Automatic Incident Detection
ASHRAE	American Society of Heating Refrigeration and Air-conditioning Engineers
CCTV	Closed-Circuit Television
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
EVS	Emergency Ventilation System
FFFS	Fixed Fire Fighting Systems
FHRR	Fire Heat Release Rate
FHWA	Federal Highway Administration
FLS	Fire-Life Safety
FPLS	Fire Protection and Life-Safety
LHD	Linear Heat Detector
MTFVTP	Memorial Tunnel Fire Ventilation Test Program
NBFU	National Bureau of Fire Underwriters
NFPA	National Fire Protection Association
NCHRP	National Cooperative Highway Research Program
PIARC	World Road Association, Permanent International Association of Road Congresses
SCADA	Supervisory Control and Data Acquisition
SFPE	Society of Fire Protection Engineers
TOMIE	Tunnel Operation Maintenance Inspection and Evaluation
U.S.	United States
VMS	Variable Message Sign

SUMMARY

The main goal of this research is to facilitate the design of the fixed fire fighting systems (FFFS) and emergency ventilation system (EVS) in an integrated manner. The introduction identified 16 questions to help focus the review and synthesis, and the responses to those questions are summarized as follows:

1. **What types of tunnels are constructed and how?**
   The four main tunnel types are circular, rectangular, horseshoe, and oval. They are constructed by boring, blasting, excavating, or by sinking a precast tube.
2. **What are the principal functional systems?**
   The principal functional systems include EVS, FFFS, closed circuit television (CCTV), public address and communications, signage, lighting, standpipe, supervisory control and data acquisition (SCADA), public address (PA), power, and drainage.
3. **What are the U.S. fire-life safety (FLS) approaches for highway tunnels?**
   The primary FLS approach for highway tunnels is compliance with National Fire Protection Association (NFPA) Standard 502 via an engineering analysis showing the FLS goals are met. For longer tunnels, this usually includes an EVS at a minimum.
4. **Where do FFFS fit into the overall FLS picture for a U.S. highway tunnel?**
   For tunnels complying with NFPA 502, FFFS should be considered as part of the overall FLS design. Historically, FFFS have had limited use in United States (U.S.) tunnels, but they are becoming more common in line with international practices.
5. **How does the tunnel construction affect the fire protection life safety (FPLS) system?**
   The tunnel construction will greatly affect the FPLS systems and their installation. For example, a transverse ventilation system cannot be used unless separate air ducts are part of the tunnel construction. FFFS and other systems are less affected by construction type. However, routing of pipework and other elements requires sufficient clearance above the roadway, space for ancillary equipment must be considered, along with supporting infrastructure to supply/remove water from the FFFS.
6. **What are the design FHRRs recommended?**
   NFPA 502 states that a representative FHRR for an HGV is 150 MW, and a flammable liquid tanker is 300 MW. These values should be used only as a starting point in determining the design FHRR for a given tunnel. The final determination of the design fire should be made after considering all relevant factors on a case-by-case basis for each tunnel (e.g. tunnel geometry, traffic makeup, facility risk, etc.).
7. **What is the impact of FFFS on FHRR?**
   The expected impact of FFFS varies with system type, application rate, droplet size, and nozzle type. However, various small and full-scale tests indicate that a reduction in peak fire heat release rate (FHRR) of 50 to 70% is likely (assuming prompt activation of the system and a water application rate of 0.15 to 0.20 gpm/ft^2, or 6 to 8 mm/min) [1] [2] [3] [4]. Information on nozzle type and impacts on the FHRR could be better documented and this is an area where further research would be beneficial. Laboratory scale testing has shown that FFFS only reduces the FHRR for liquid fuel spills if an aqueous film forming foam (AFFF) is added [5].

8. ***How do different types of FFFS and their activation and application rates affect the fire?***
   Droplet diameter varies between deluge and mist systems. Mist systems tend to provide greater temperature reduction, but deluge systems have a greater ability of reaching and cooling the burning surface. Water mist droplets are unable to penetrate the fire plume and reach the seat of the fire. For shielded fires water spray cannot reach the seat of the fire and thus performance is similar between deluge and mist.

   Delayed activation of FFFS limits the reduction in peak FHRR achieved [6]. Typically, a higher water application rate results in a slightly lower peak FHRR [2] [3]. However, for deluge system water application rates of 0.15 gpm/ft^2 (6 mm/min) and greater, the difference in peak FHRR (e.g. between 0.15 gpm/ft^2 and 0.20 gpm/ft^2) is small and unlikely to be of significance for integrated FFFS-EVS designs.

9. **What is the role of laboratory scale testing and full-scale testing?**
   Combustion modeling remains a heavily researched topic, and the full physics of combustion are not completely understood. Generating experimental data in full and small-scale tests allows theories to be tested, computational fluid dynamics (CFD) models to be calibrated, and other practical insights to be gained about how fires burn in tunnels.

10. **What is the role of computational fluid dynamics (CFD) modeling?**
    CFD models are a relatively quick and cost effective means of investigating a particular fire scenario in a tunnel where the FHRR is specified a priori. CFD can be reliably used to predict gas phase cooling. However, for FHRR or fire spread prediction, in order to draw any useful conclusions from a model, it must be calibrated against experimental data. CFD also has a limited ability to model certain aspects of FFFS in tunnels (e.g. FFFS interruption of the combustion/pyrolysis process).

11. **How do water application rate and other design parameters link to NFPA 502 goals?**
    As per Table 4-4, the water application rates (with deluge systems) of 0.30 gpm/ft^2 to 0.15 gpm/ft^2 (12 mm/min to 6 mm/min) could achieve fire control. No water application achieved fire suppression unless the fire was sufficiently exposed such that water application could directly reach the seat of the fire. Recent data suggest water application rates as low as 0.05 gpm/ft^2 (2.2 mm/min) could achieve control. Further study with testing or analysis (CFD) is needed to better quantify threshold limits and system details (nozzle layout, type, water application rate) with respect to NFPA 502 goals.

12. **What level of effort is needed for maintenance and inspection of FFFS?**
    Regular maintenance and inspection of FFFS are critical to their effective operation. On average, FFFS have a high effectiveness value [7]. Maintenance requirements for FFFS are outlined in NFPA 25 [8]. Many valve components need weekly or monthly inspections; however, the sprinkler piping and nozzles only need annual inspections. Based on data from thousands of fire events, the reliability rate of a properly designed, maintained, and operated FFFS is 99.4% [9].

13. **What is the deflection of water droplets by the EVS?**
    Generally, not a concern, if multiple zones can be activated, refer to Section 5.3.7. A validated modeling methodology for water spray drift would be useful.

14. Is there a critical velocity equation that is applied when the FFFS are applied?
One equation has been derived, based on test data, refer to Section 5.3.2. Figure 5 19 provides a correlation but the FHRR is limited to a maximum of 40 MW. For FHRRs greater than 40 MW, there is no specific equation for critical velocity with FFFS applied, and it is necessary to use CFD modeling or testing.

15. Where are the vulnerable points in an integrated FFFS-EVS design?
Research needs due to vulnerability include:

- Develop a more general equation for critical velocity with ventilation and FFFS using CFD modeling.
- Pressure loss caused by the FFFS components and FFFS spray (droplets and humidity) – investigate with testing and analytical sums
- Pressure loss caused by the fire when an FFFS is operating.
- FFFS impact on FHRR – agree on a nozzle type and water application rate for a certain FHRR outcome.
- In terms of tenability for occupant egress, further information would be useful as follows:
  - Additional data on heavy goods vehicle (HGV) toxic gas yields.
  - Measurement of irritant species for a fire with and without FFFS.
  - Timing for egress, FFFS activation, fire growth, etc.

16. Do FFFS reduce the structural passive fire protection requirements *(arising per NFPA 502)*; if so, by how much, and how does system reliability impact this?
It is demonstrated that FFFS can reduce the FHRR and hence the temperatures that the structure is exposed to. The degree of cooling will depend on the FFFS parameters as well as the fire source. CFD analysis can be used to characterize the thermal environment and to determine a suitable time-temperature curve for structural design. There is a strong coupling between the thermal environment analysis and the subsequent structural design, and coordination is critical. Passive fire protection requirements can be reduced, but key considerations include the thermal response of the concrete, the risk of structural failure (e.g. failures may be less tolerable if the tunnel is in unstable ground) and FFFS reliability. There is still a potential for spalling even with the use of FFFS; the delayed activation of FFFS allows concrete temperatures to increase, which is then coupled with thermal shock after the application of cooler water. A failure of the FFFS system will also increase the likelihood of spalling.

The subject of FFFS reliability when considering compensations for passive fire protection is an area for further research and development. It is important to understand the consequences of FFFS failure for a structure relying on active fire protection, and the likelihood of FFFS failure. Ultimately, compensation of passive fire protection based on FFFS inclusion requires a consensus on an acceptable level of residual risk.

Relevant to the basic goal of this research, the following key areas are identified for further investigation as part of the computer modeling and testing (laboratory and full-scale) efforts:

- Critical velocity:
  - Critical velocity is of interest because the ability to predict critical velocity when an FFFS is operated is the most fundamental input to an integrated EVS design. Existing equations have limited validity at high FHRRs. The goal for further investigation is to develop a validated and verified method of modeling tunnel fires to determine critical velocity with FFFS, and to extend the range of validity of existing equations.
- Transverse ventilation:
  - Transverse ventilation is of interest because many existing tunnels in the U.S. use a transverse ventilation system. Of concern is how smoke management in a transverse scheme is affected by the FFFS, as well as whether FFFS droplets can be entrained in the exhaust airflow and lower the effectiveness of the FFFS. The laboratory testing and full-scale testing, which is planned to follow the computer modeling, is focused to provide test data for validation of models and equations.

Most new tunnels in the U.S. are using a longitudinal EVS via the action of jet fans. Section 5.3 described a design approach where a one-dimensional calculation is used to compute the fan thrust requirements. As part of that review several key parts of the calculation where the FFFS has an impact were identified. The summary below notes where further research is proposed as part of this research effort and the contributions that are anticipated:

- Fire heat release rate (Section 5.3.1):
  - The impact of FFFS on the FHRR is well-established from full-scale tests. Measurements of FHRR (laboratory and full-scale) will provide useful additional data to further confirm the efficacy of the FFFS for a given water application rate and nozzle layout/type.
- Critical velocity for smoke control (Section 5.3.2):
  - Detailed modeling and testing investigation is proposed as per the discussion above.
- FFFS cooling of the combustion products (Section 5.3.3):
  - The ability of the FFFS to cool combustion products is well-established. Critical velocity research, modeling and testing (measurement of temperatures), will provide additional data to further the knowledge in this area.
- Pressure loss (airflow resistance) due to fire (Section 5.3.4):
  - Equations have been developed for pressure loss due to fire. Measurements of static pressure (laboratory and full-scale) upstream and downstream of the fire will provide useful additional data to further confirm validity of the equations and to understand the FFFS impacts.
- Pressure loss (airflow resistance) due to the FFFS (droplets and humidity) (Section 5.3.5):
  - Measurements of pressure loss and humidity in the full-scale and laboratory scale tests will provide useful data for validation of analytical calculations. Cold flow measurements will provide useful data related to droplet drag.

- Friction losses introduced by FFFS pipework (Section 5.3.6):
  - Measurements of cold flow in the full-scale and laboratory scale tests with ventilation operating will provide useful data for validation of friction to due FFS pipework.
- Water droplet deflection due to the EVS (Section 5.3.7):
  - Cold flow measurements will provide useful data related to droplet drift due to ventilation. Computer modeling for droplet drift will provide useful data for validation of a model to investigate transverse ventilation and droplet entrainment.
- Tenability for egress and fire fighting (Section 5.3.8):
  - The impact of the FFFS on generation of carbon monoxide is such that the yield of CO is increased due to incomplete combustion. Measurement of carbon monoxide (CO) will provide useful data to help further verify this result. Measurement of irritant gas concentrations, although not a primary focus of this work, would provide useful additional data for future computer model development.

Additional topics that merit further investigation include:

- Impact of external wind on conditions inside the tunnel and contribution to fire growth rate or impact on FFFS performance.
- Further work to understand spalling and predict spalling, thus allowing an analysis to consider spalling potential following a delay in the FFFS operation.
- Further work to look at whether there are any interactions between spalling and FFFS operation.

ACKNOWLEDGEMENTS

The FHWA would like to acknowledge the following organizations and individuals for providing review and comment on this literature survey and synthesis:

- American Association of State Highway and Transportation Officials (AASHTO)
- American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE)
- National Fire Protection Association (NFPA)
- Soundar Balakumaran (Virginia Department of Transportation)
- A Calado (Jacobs)
- Nigel Casey (RMS, Australia)
- Mun Kit Cheong (Land Transport Authority (Singapore))
- Gary English (UCS)
- Haukur Ingason (RISE Safety)
- Bijan Khaleghi (Washington State Department of Transportation)
- Ray Klein (Jacobs)
- Yoon Ko (National Research Council Canada)
- Ying Zhen Li (RISE Safety)
- Igor Maevski (Jacobs)
- Albert Nako (Oregon Department of Transportation)
- Bradley Weidenhammer (Virginia Department of Transportation)

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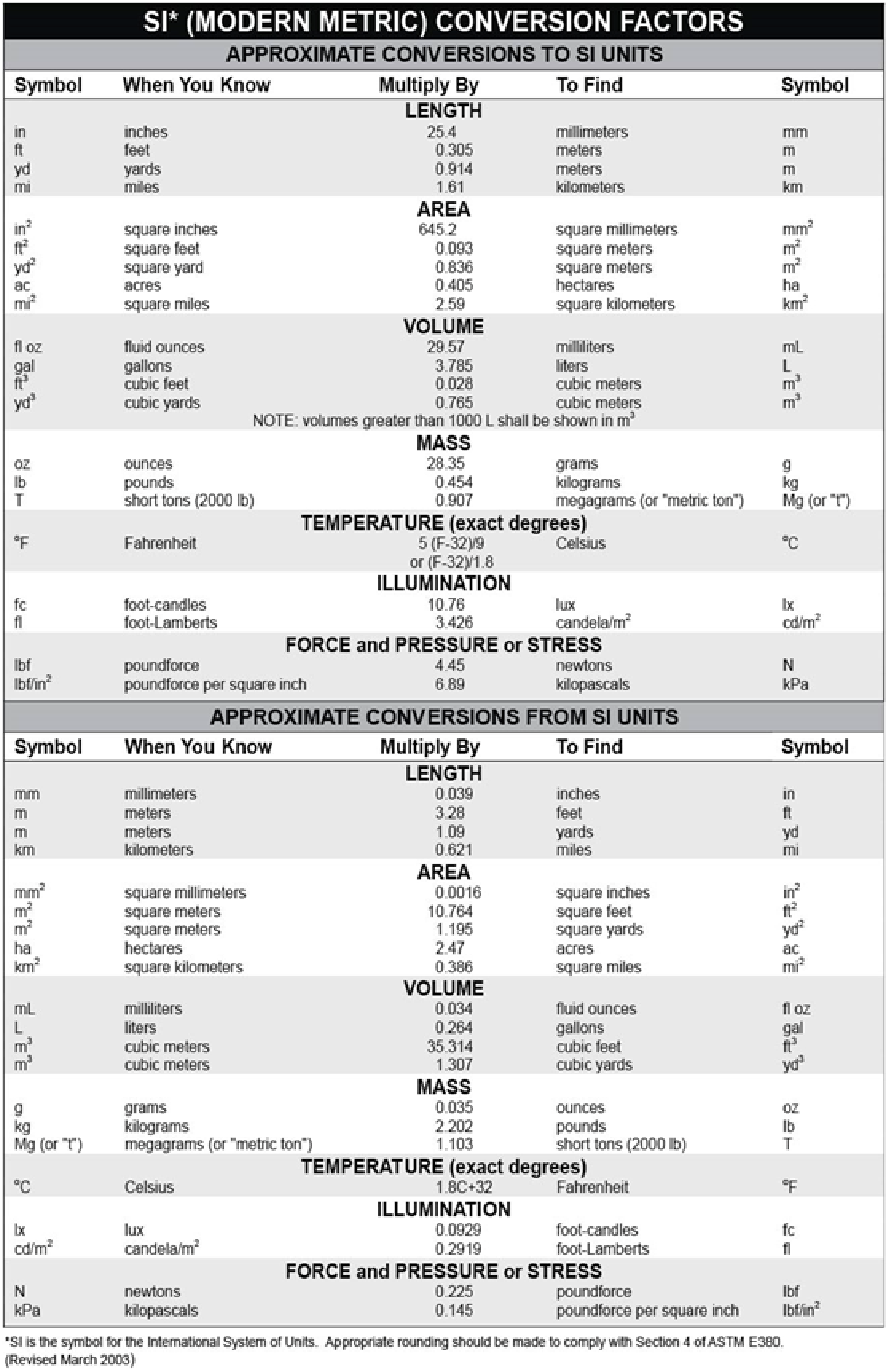

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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1 INTRODUCTION

In 1956 the National Board of Fire Underwriters (NBFU) published standard number 502 titled *Fire Protection for Limited Access Highways, Tunnels and Bridges*. This document was the precursor to the modern-day standard *NFPA 502: Standard for Road Tunnels, Bridges and Other Limited Access Highways*. The NBFU document recommended that "consideration be given to the installation of an automatic sprinkler system." At some point after publication of NBFU 502, the industry shifted away from using sprinklers and other forms of fixed fire fighting systems (FFFS) in road tunnels. In the 2001 edition, the NFPA 502 annex recommended that "sprinkler systems should be considered only where the passage of hazardous cargo is considered." Several large, non-hazardous goods, fires in Europe around the year 2000 highlighted the potentially deadly consequences of fire in a highway tunnel. These events, coupled with successful implementation of FFFS in Japan and Australia, has led to reconsideration of FFFS as both a life safety and resiliency feature for highway tunnels in the United States. NFPA 502 now recognizes that FFFS should be considered as part of a highway tunnel's overall fire protection and life safety plan, and the recent trend is toward FFFS being a routine installation in highway tunnels.

There is a lot of global experience with FFFS, particularly in Australia and Japan, but also in several recently constructed tunnels in the United States and Europe. The U.S. first implemented FFFS in their tunnels in the 1950s, however, this approach did not become routine, partly due to unsuccessful tests of FFFS in the Offneg Tunnel in Europe [10]. Because FFFS were not routinely applied in all tunnels, the present-day approach can vary between planned facilities and regions, especially in critical design areas such as operational integration with the EVS. Recent testing, fire incidents, and modeling efforts have demonstrated that FFFS lessen the fire hazard by cooling combustion products and (in certain circumstances) suppressing the fire (reducing the fire heat release rate [FHRR]). Further research and a design-focused approach to computational modeling and testing is needed to develop a set of industry suggested practices on the integration of FFFS and the EVS. The end goal of the research is to facilitate design of the FFFS and EVS in an integrated manner. This would then help the industry to realize the full benefit of providing FFFS in new and existing tunnels in the U.S.

A significant amount of data exists on the topic of FFFS and EVS design for highway tunnels, including journals, conference proceedings, test programs, design guidelines, operational experience, and industry practice. This document presents a literature review and synthesis to summarize the current state of practice. The following questions were posed to guide the focus of the review:

1. What types of tunnels are constructed and how?
   Refer to Chapter 2.

2. What are the principal functional systems?
   Refer to Chapter 2.

3. What are the U.S. FLS approaches for highway tunnels?
   Refer to Chapter 2.

4. Where do FFFS fit into the overall FLS picture for a U.S. highway tunnel?
   Refer to Chapter 2.

5. How does the tunnel construction affect the FPLS system?
   Refer to Chapter 2.
6. What are the design FHRRs recommended?
   Refer to Chapter 3.
7. What is the impact of the FFFS on the FHRR?
   Refer to Chapter 3.
8. How do different types of FFFS and their activation and application rates affect the fire?
   Refer to Chapter 3.
9. What is the role of laboratory scale testing and full-scale testing?
   Refer to Chapter 3.
10. What is the role of CFD modeling?
    Refer to Chapter 3.
11. How do water application rate and other design parameters link to NFPA 502 goals?
    Refer to Chapter 4.
12. What level of effort is needed for maintenance and inspection of FFFS?
    Refer to Chapter 4.
13. What is the deflection of water droplets by the EVS?
    Refer to Chapter 5.
14. Is there a critical velocity equation that is applied when the FFFS are applied?
    Refer to Chapter 5.
15. Where are the vulnerable points in an integrated FFFS-EVS design?
    Refer to Chapter 5.
16. Do FFFS reduce the structural passive fire protection requirements (arising per NFPA 502); if so, by how much, and how does system reliability impact this?
    Refer to Chapter 6.

This document is arranged as follows:

- Chapter 2 – Tunnel Design and Fire-Life Safety – Overview of US highway tunnel design including geometry, structure (construction and materials), tunnel systems (ventilation, power, drainage, FFFS, lighting, traffic control, CCTV), maintenance and inspection (TOMIE manual), and standards. Project delivery method, review of NFPA 502 (including role in the design process, content and main requirements, application in U.S. jurisdictions, past, present and future content, trends and considerations), practitioner requirements (education, skills, qualifications, licensing), design and approval process (role of stakeholders – owners, agencies, fire department, public, subject matter experts), construction, commissioning and operation (procedures for FFFS and EVS activation, emergency plans, exercises, false operation, training), and perspectives on the balance between safety, resources and performance of various FLS systems.

- Chapter 3 – Tunnel Design Fires – Fire dynamics (fire growth rate, heat release rate, fire spread) for design fire loads including cars, heavy goods vehicles, hazardous vehicles (including tankers) and new energy carriers (electric vehicles, hydrogen vehicles), impact of FFFS on the fire, testing programs, tunnel geometry influence, CFD modeling approaches, and documented fire incidents involving FFFS, including system reliability consideration.
- Chapter 4 – FFFS Design and Performance – In line with NFPA 502, areas include fire suppression, over-height vehicle protection, fire control (prevention of spread), cooling (volume and surface) and how achieving these performance goals relates to key FFFS design parameters including water application rate, reliability, nozzle design. How modeling, testing and research are used to develop designs, as well as how different systems are integrated with or without the FFFS.
- Chapter 5 – FFFS-EVS Interaction – Ventilation performance requirements and types of EVS (transverse, longitudinal, point exhaust), design fires, modeling (equations for critical velocity, 1D models, CFD models), EVS design guidelines, and FFFS influence on fan performance.
- Chapter 6 – FFFS and Tunnel Structure – Design fire heat release rate with and without FFFS operation, cooling the products of combustion, time-temperature curve (RWS (Rijkswaterstaat) and other curves), ceiling geometry, structural coordination (allowable temperatures), concrete properties, spalling and addition of PP fibers, and role of testing, analysis and modeling.
- Chapter 7 – Summary

1.1 Limitations

Hazardous materials and FFFS impacts, including liquid fuel fires and FFFS impacts, are discussed herein. However, detailed investigation of the management of hazardous goods fires with FFFS is a much more complex topic that is not part of the primary scope of work, which is integration of the EVS and FFFS. For this reason, the review focuses mostly on heavy goods vehicle fires without hazardous cargos, and the interactions between the EVS and FFFS.

Regarding foam additives, where this document refers to an FFFS it will implicitly refer to a water only FFFS. If a foam additive is applicable or present, then this will be explicitly stated in the discussion.

1.2 Terminology

In the industry, numerous terms are used in the description of FFFS. The following definitions are provided in NFPA documents related to FFFS:

- **Deluge sprinkler system** – A sprinkler system employing open sprinklers or nozzles that are attached to a piping system that is connected to a water supply through a valve that is opened by the operation of a detection system installed in the same areas as the sprinklers or the nozzles. When this valve opens, water flows into the piping system and discharges from all sprinklers or nozzles attached thereto (NFPA 13).
- **Deluge system** – An open fixed water-based fire suppression system activated either manually or automatically (NFPA 502).

- **Fixed water-based fire-fighting system** – A system permanently attached to the tunnel that is able to spread a water-based extinguishing agent in all or part of the tunnel (NFPA 502).
- **High pressure system** – A water mist system where the distribution system piping is exposed to pressures of 34.5 bar (500 psi) or greater (NFPA 750).
- **Water mist system** – A water spray for which the Dv0.99, for the flow-weighted cumulative volumetric distribution of water droplets is less than 1000 μm within the nozzle operating pressure range (NFPA 750).

  Although a water mist system is technically a deluge sprinkler system (per NFPA 13), in the tunnel industry, the terms for deluge system and water mist system have a subtle difference between their meaning, and in line with PIARC [11] the following definitions will be used throughout this document:

  - The term **deluge system** refers to lower pressure large water droplet deluge systems (typical water pressures in the order 1 bar to 1.5 bar, droplet diameter in the order 1000 μm or greater).
  - The term **water mist system** is associated with a deluge system that employs a large water pressure and special nozzles to generate a very small droplet diameter (typical pressures 16 bar to 60 bar, droplet diameter in the order 400 μm to 200 μm).
  - Systems that employ frangible bulbs in the nozzles will be referred to as **automatic sprinkler systems**.

2 TUNNEL DESIGN AND FIRE-LIFE SAFETY

A road tunnel is defined by the FHWA as:

> An enclosed roadway for motor vehicle traffic with vehicle access limited to portals, regardless of type of structure or method of construction, that requires, based on the owner's determination, special design considerations to include lighting, ventilation, fire protection systems, and emergency egress capacity.

To guide the design of the tunnel FLS systems, many jurisdictions adopt NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways [12], making it a legal requirement where formally adopted. NFPA 502 is primarily a performance-based standard, identifying the goals of a system and allowing the engineer to design a system meeting these goals.

Developing an integrated fire protection life safety (FPLS) system design involves coordination between a variety of responsible parties and design elements. The design elements each party is responsible for are summarized in Table 2-1. These are then further detailed in the following subsections. Topics include the present state of tunnel and FPLS design, including: common tunnel types, supporting tunnel systems, an overview of NFPA 502, the design process, and the use of FPLS in existing tunnels.

Table 2-1: Components of an integrated fire protection and life safety system design.

Area	**Design and operation elements for integration**
Mechanical engineering design	FFFS and EVS
Electrical engineering design	CCTV, fire alarm, SCADA, traffic control
Civil engineering design	Structure, drainage, traffic
Stakeholder – owner / operator	Maintenance and emergency response, inspection and preservation
Stakeholder – first responders	Response planning and training
Fire protection and life safety	Includes parts of the design disciplines – electrical, mechanical and civil as they relate to fire impacts

2.1 Tunnel Design and Construction

2.1.1 Geometry

The tunnel shape is defined by the exterior of the tunnel, which is generally determined by the method of construction. Most tunnels have a rectangular interior for traffic. The geometry of the tunnel can vary along the length of a single tunnel. The changing of cross-sections generally is the result of a change in the tunneling method along the length of the tunnel. The four common highway tunnel shapes per the Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) manual are listed in Table 2-2.

Table 2-2: Common tunnel shapes [13].

Tunnel shape	**Comments**
Circular	Rectangular roadway cross section with raised walkway on either side. Space above and below the roadway can be used as ventilation plenums. A tunnel ceiling is present in certain designs. Subset of this geometry is a twin-level tunnel; one level in each direction of travel (e.g. Alaska Way Tunnel in Seattle). Typical construction method: tunnel boring machine. Refer to Figure 2-1.
Rectangular	Allows for unidirectional traffic in two tunnels or bidirectional traffic in a single tunnel. All interior volume is used for the roadway. Typical construction method: immersed tube or cut and cover. Refer to Figure 2-2.
Horseshoe	Combination of circular and rectangular tunnels, with one void above the roadway that can be used as a ventilation plenum. A tunnel ceiling is present in certain designs. Typical construction method: mined or excavated. Refer to Figure 2-3.
Oval	Wider version of the horseshoe tunnel, which allows for more lanes of traffic. Oval shape can also be used to better withstand pressures (e.g. ground or groundwater). A tunnel ceiling is present in certain designs. Typical construction method: mined or excavated. Refer to Figure 2-4.

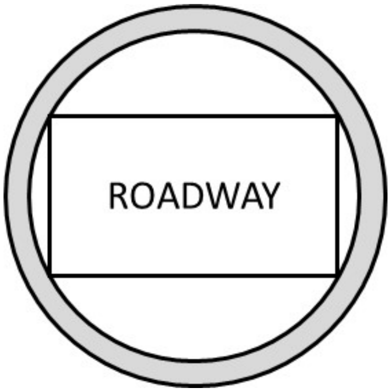


Figure 2-1: Circular cross-section tunnel.

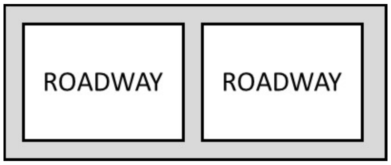


Figure 2-2: Rectangular cross-section tunnel.

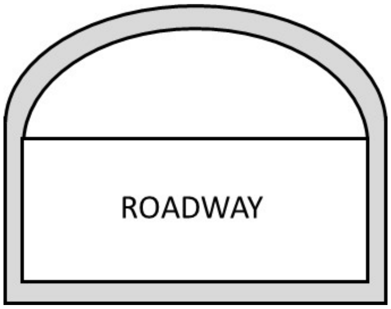


Figure 2-3: Horseshoe cross-section tunnel.

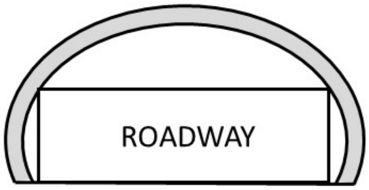


Figure 2-4: Arch cross-section tunnel.

2.1.2 Tunnel Construction and Materials

The method used for creating a tunnel is predicated upon the ground conditions and the location of the tunnel. The most common methods for tunneling are listed in Table 2-3.

Table 2-3: Common tunnel construction methods [13].

Construction type	Tunnel shape	Comments
Cut and cover	Rectangular	Cut and cover construction involves excavating a trench, then building the tunnel structure within the trench (typically with cast-in-place concrete). This method is best for shallow construction.
Bored	Circular	Bored tunnels are constructed using a tunnel boring machine (TBM). A rotating cutter head bores the tunnel opening. A cast-in-place liner can be placed after the boring is complete.
Immersed tube	Rectangular	Precast concrete tunnel segments are built in a dry dock, with a bulkhead at each end. The segments are towed to site and sunk into place. The segment is drained, the segments are joined, and bulkheads removed.
Drill and blast	Horseshoe, oval	Holes are drilled in the tunnel face, filled with explosives, and detonated. Tunnel is finished with a cast-in-place liner.
Sequential excavation	Horseshoe, oval	Tunnel is excavated in stages, most often used in soft ground and poor rock conditions for short tunnels. The tunnel is finished with a cast-in-place liner.

2.2 Tunnel Functional Systems

The following table gives an overview of the supporting mechanical, electrical, and plumbing systems typically relied on to safely operate a tunnel.

Table 2-4: Tunnel functional systems table.

System function and type	Role in overall FPLS design	FFFS-EVS integration considerations
Fire prevention – height control	Prevents over-height vehicles from damaging ceiling mounted systems	Not applicable
Fire prevention – hazardous vehicle restrictions	The range of vehicle types allowed to use the tunnel affects the design fire used in the overall FPLS design; the tunnel owner needs to enforce review of the facility to respond to changes in vehicle types over time	The effectiveness of the FFFS on a vehicle/cargo type should be considered when designing the EVS

System function and type	Role in overall FPLS design	FFFS-EVS integration considerations
Detection – CCTV cameras	Cameras allow a tunnel operator to remotely monitor conditions and identify incidents Cameras can be fitted with video incident detection systems which can alert an operator to a problem early during an incident Cameras can be fitted with smoke, flame and heat detection although this is not commonly used as a primary means of detection	Because fires are often detected via CCTV before an automatic fire detection system alarms, the operator should use the CCTV to identify the fire location; fire modes and FFFS zones should be considered when locating cameras (e.g. at zone boundaries)
Detection – automatic incident detection (AID) via CCTV	AID implementation on a CCTV system quickly alerts an operator to stopped vehicles within the tunnel	AID imposes requirements on the camera spacing (see further coordination requirements for CCTV above)
Detection – linear heat detection	Linear heat detection (LHD) is a fusible type cable that is set to activate at a certain temperature or based on a rate of rise; it provides an automatic means of detecting a fire and its location	The LHD alarm should be coordinated with the SCADA system to activate the appropriate zoned response based on the fire location
Detection – traffic loop detection	Can alert the operator to a stopped or slowed traffic condition, like AID on CCTV	Not applicable
Detection – alarms (doors, cabinets, etc.)	Access control and monitoring is important to ensure the local FPLS controls are not tampered with	Not applicable
Egress – exits	Emergency exits and signage directing users to them provide a point of safety for users and an access point for first responders	The spacing of exits should be considered during the FPLS design, as they change the egress path and time of tenability required
Egress – lighting	Lighting in road tunnels is often required to comply with IES RP-22, which gives normal and emergency light levels; lighting is also used to illuminate egress points and other signage	Egress lighting should be coordinated with fire modes to illuminate the best egress path; activation of FFFS will also reduce visibility of lights
Egress – low level lights	Low level lights outline lanes and barriers	Activation of FFFS will reduce visibility of lights
Egress – exit sounders	Exit sounders are located at egress doors and announce the exit point	Both FFFS and EVS will generate significant in-tunnel noise, making exit sounders difficult to hear
Communications – public address system	The PA system relays information to users during an incident and can also be used to initiate an evacuation	Noise from the FFFS and EVS will significantly affect the intelligibility of the system
Communications – emergency phones	Phones placed along the tunnel allow users to report incidents and provide detail; these are useful where phone service coverage is poor	Not applicable

System function and type	Role in overall FPLS design	FFFS-EVS integration considerations
Communications – cell phone / radio rebroadcast	Phone service and radio signal strength are reduced in a tunnel; the addition of rebroadcast systems allows motorists and first responders to communicate	Not applicable
Communications – variable message signs	Variable message signs (VMS) and lane use signals allow the operator to control traffic; VMS can also be used to transmit specific messages to users	VMS messages should be coordinated with fire mode operation to alert motorists to FFFS activation (driving hazard exists due to low visibility)
Smoke management – jet fans and smoke exhaust	Fans keep the egress path clear of smoke and hot gases	The ventilation system should be designed based on the design fire and considering the effects of FFFS on it
Fire protection – hydrants	Hydrants provide a fire department connection to a water supply that can be used to charge a standpipe or attach a hose and fight a fire directly	Not applicable
Fire protection – hose connections	Hose connections to a standpipe within the tunnel allow firefighters to operate at locations remote from a hydrant; may include points for inserting foam	The local fire department will have requirements on the hose connection type and may request the standpipe, if dry, be automatically charged during a fire mode
Fire protection – extinguishers	Extinguishers are typically provided at regular intervals along the tunnel and are useful for control of very small fires	Not applicable
Fire protection – water supply	Depending on the location of the tunnel, the local water supply may not be sufficient to support FFFS or standpipe; storage tanks and pumps may be necessary to meet the requirements	The available water supply will significantly affect any FFFS design, especially the water flow rate and subsequent cooling/reduction of the design fire
Fire protection – FFFS	FFFS are one of the critical elements in the FPLS design, and can significantly affect the design fire and the tunnel structural protection required	FFFS should be designed considering the effects of an EVS
Passive fire protection – structural fire rating	Depending on the design fire, additional structural protection may be needed to maintain the integrity of the tunnel for a set period Where used with FFFS present, the protection needs to be waterproof such that the FFFS will not damage it	Passive fire protection allows less heat transfer to walls; however, the impact on EVS requirements is negligible [14]
Electrical – redundant power supply	Tunnels should have redundant power supplies capable of powering the emergency systems if the tunnel is to remain open during a power outage; this can be done with independent power feeds, generators, and uninterruptible power supplies	The redundant power supply sizing should consider the feasibility of powering any FFFS and EVS systems

System function and type	Role in overall FPLS design	FFFS-EVS integration considerations
Electrical – redundant control	If the connection is lost between the main tunnel control center and the tunnel, a second control center is provided as a backup	Any FFFS and EVS systems should be controllable from the backup control center
Drainage – roadway drains	A roadway drainage system is important for keeping the roadway clear of pooling water, including capturing water from FFFS and fire fighting activities, and preventing fire propagation through the drainage system	The drainage system should be sized with FFFS application rate in mind, as well as the volume of water expected due to tunnel leakage, a spill from cargo, and an allowance for hose streams
Management and response – response crew	The response crew is tasked with initial response to incidents, including fighting small fires	The response crew must be trained on the response procedures for fire incidents, including what to expect during FFFS and EVS operations
Management and response – control center	The control center and the assigned tunnel operators are responsible for monitoring the tunnel and initiating the fire response procedures Not all tunnels have a dedicated control center and full time operator; where an operator is not present, local controls (for fire department to operate FFFS and EVS) and automation of a response are needed	The FFFS and EVS controls should be designed with the tunnel operator in mind, and should be as straightforward as possible to limit confusion during a stressful incident
Management and response – incident response	As part of any FPLS design, a response procedures document is produced with input from local authorities and first responders; the response timeline should be considered during design of FFFS and EVS systems	Not applicable

2.3 Operational Aspects

This section discusses the operational aspects of FPLS systems, including activation, emergency response, and maintenance.

2.3.1 System Activation

There are three means of activating FFFS and the EVS:

- Automatic – an alarm signal to the controls system (SCADA) activates the appropriate FFFS/EVS response immediately. This signal could come from a LHD, individual heat/smoke detectors, and AID via a CCTV system.
- Semi-automatic – an alarm signal to the controls system (SCADA) alerts an operator, who can manually override/activate FFFS/EVS response before the system automatically responds. This signal could come from a LHD, individual heat/smoke detectors, and AID via a CCTV system.
- Manual – activation of FFFS/EVS is by a human operator. The operator typically views an incident on CCTV and determines the appropriate response from there. Manual activation could also come from valves within the tunnel.

A design is not limited to just one activation method; it could be comprised of a primary manual operation mode with backup semi-automatic/automatic modes in case the operator is unresponsive. These response modes are detailed in a facility-specific emergency response plan document (further discussed in Section 2.3.2).

In addition to the intended means of activation, FFFS can be activated unintentionally as well. This is typically due to false operation of the system, either through system fault or a maintenance accident. There is also the rare possibility of activation by a trespasser who gains access to the deluge valves. False activation can lead to a tunnel closure while the incident is investigated and the FFFS are turned off [15].

2.3.2 Emergency Response

NFPA 502 Chapter 13 provides high-level requirements for emergency response planning and training. NFPA 502 notes that the agency responsible for operation of the facility needs to anticipate and plan for emergencies that could affect the facility and that it needs to incorporate feedback from local first responders, agencies, and the designers. The response plan also needs to consider the available FPLS operational modes and their control interface. NFPA 502 does not dictate the specifics of response, it only gives suggested considerations.

Some typical aspects of a tunnel fire incident are as follows. A tunnel fire usually begins with a stopped vehicle, which for manual responses is noted by the tunnel operator via a CCTV system. As the fire grows, smoke and flame will be visible. The emergency response plan should define at which point the operator will activate the EVS and FFFS. This will depend on the design fire, the FPLS design, and first responder input. A tunnel operator will (typically) activate the FFFS if they perceive there is a fire [15]; this could be triggered by visible smoke or flame (on CCTV) or a heat detector activation. This response needs to be balanced with the fact that the activation of FFFS reduces roadway visibility. Because of this, the FFFS are not normally activated until the incident vehicle is stopped and surrounding traffic is moving slowly (ideally stopped). For automatic responses, activation of the FPLS systems is typically triggered by a heat detecting device.

An important aspect of the emergency response is the planning and training. Tunnel operations staff need to be trained in how to operate the FPLS systems and the response procedures. NFPA 502 also requires that at least twice a year, exercises and drills take place between all involved agencies. The exact form of an exercise or drill is subject to authority having jurisdiction (AHJ) approval per NFPA 502.

2.3.3 Operational Response Integration

When considering the emergency response, the importance of the operator's interface to the FPLS systems should not be overlooked. During an incident, the operator must make decisions and act within a short period, all during a stressful situation. Table 2-5 lists the decisions an operator may have to make, and Table 2-6 the actions an operator may have to take, during a fire incident in a tunnel equipped with FFFS and EVS.

To reduce the stress on the operator, a "one button response" can be used to integrate the controls for all FPLS systems. This means that the system is configured to automate many of the actions in Table 2-6 once the operator answers the decision questions in Table 2-5. The operator then has more capacity to communicate with emergency responders and monitor the incident while the system activates the appropriate systems in the correct order. A "one button response" can be staged, such that critical actions that have minimal adverse impact on motorists, such as EVS and traffic control, are implemented as soon as a fire is suspected, and then FFFS are operated as a second step once the operator confirms a fire and has implemented necessary traffic management. Note that although this involves two steps, the principle of the "one button response" is maintained if operator actions are minimal (i.e. just answering basic questions) at each step.

This "one button response" also minimizes the chance of operators "locking up" during the incident by guiding them through incident response process. Because incidents are relatively infrequent, an operator may not have a lot of practice deploying the systems [16].

Training is an important part of FPLS operations. As an example, Australia currently has a certification process for tunnel operators, ensuring that its operators can successfully operate all the FPLS systems and are well-versed in competencies including: first aid, environmental compliance, safety management, communications, and quality. The training program requires coursework and three to six months of study. Operators must renew their certification regularly. This certification process has emphasized tunnel safety and the important role operators have in safety [15]. Other training programs may exist in the U.S. and internationally, but no programs with a formal qualification are known at present.

Table 2-5: Operator typical responsibilities during incidents – decisions.

Decisions
Is there smoke or fire?
Where in the tunnel is the incident?
Activate the EVS?
Activate the FFFS?
What FFFS zone is it?
Evacuate the tunnel?

Table 2-6: Operator typical responsibilities during incidents – actions.

Actions
Call 911 and talk to the dispatcher
Dispatch tunnel operations crew
Close the tunnel
Set warning messages on VMS
Charge the standpipe
Activate the EVS
Activate the FFFS
Activate PA announcements
Activate egress lighting
Monitor the incident

2.3.4 Maintenance

FFFS involve regular maintenance to ensure the system functions as designed, which includes inspections and testing. For components over the roadway, this involves a lane or road closure and is typically done at night to minimize impacts to traffic. When designing FFFS, an effort should be made to place valves and other equipment in a location where closures aren't necessary to perform inspections. The PIARC guide to FFFS in road tunnels gives suggested maintenance activities and frequencies [11]. For U.S. tunnels maintenance frequencies are provided per NFPA 25 Standard for the Inspection Testing and Maintenance of Water-Based Fire Protection Systems [8].

2.4 Design of Fire-Life Safety Systems and NFPA 502

In the U.S., most projects follow NFPA 502 to develop the FPLS design. This section details the use of NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways in the design of road tunnels.

2.4.1 History of the Standard

In 1956 the NBFU published standard number 502 titled Fire Protection for Limited Access Highways, Tunnels and Bridges. This document was the precursor to the modern-day NFPA 502: Standard for Road Tunnels, Bridges and Other Limited Access Highways. The NFPA 502 standard was first developed in 1972, before being completely rewritten as a recommended practice document in 1980. The document underwent another overhaul in 1998 to become a standard. Additional significant revisions occurred in the early 2000s [12]:

- 2001 edition: technical changes to communication, lighting, egress, and ventilation
- 2004 edition: requirements for structural fire resistance rating for tunnels, Annex A material on FHRRs
- 2008 edition: categorization of road tunnels added, significant changes to FFFS recommendations
- 2011 edition: performance based design recommendations added, chapter on FFFS design added
- 2014 edition: changes to emergency ventilation requirements
- 2017 edition: revisions to design considerations list, revised noise level information, annex information provided on the effect of FFFS on the FHRR

As a standard, much of NFPA 502 contains mandatory provisions. When NFPA 502 is adopted by the local jurisdiction, these provisions must be adhered to during design (or variances submitted). A standard differs from recommended practice in that a recommended practice document is a non-mandatory guideline for design.

The standard is reviewed and revised every three years by the NFPA 502 technical committee. The cycle begins with a 5-month public comment period where proposed changes are submitted by the public and committee members. The NFPA 502 committee then reviews and votes on all proposed changes, incorporating (fully or partially) or rejecting the change. The revised document is reissued for public comment and comment resolution for another 5 months. After this, the revised standard is issued for publication [17].

2.4.2 Design Process of FPLS Systems

For most road tunnels in the U.S., NFPA 502 is used as the governing design standard. Project agreements may also mandate additional requirements that must be met by the design. The requirements typically include the design fire size, and the addition of FFFS or EVS.

In NFPA 502 and project agreements, there are two types of design criteria: performance based criteria and prescriptive based criteria. The SFPE Engineering Guide to Performance Based Fire Protection defines these as follows [18]:

- **Performance-based design option.** An option within a code where compliance is achieved by demonstrating through an engineering analysis that a proposed design will meet specified fire safety goals. More specifically, fire safety goals and objectives are translated into performance objectives and performance criteria. Fire models, calculations, and other verification methods are used in combination with the building design specifications, specified fire scenarios, and specified assumptions to determine whether the performance criteria have been met, which proves compliance with the code under the performance-based design option.
- **Prescriptive-based design option.** An option within a code where compliance is achieved by demonstrating compliance with the specified construction characteristics, limits on dimensions, protection systems, or other features.

Much of NFPA 502 contains performance-based requirements. Before starting the design process, the performance criteria should be clearly stated and agreed upon with the AHJ. These will form the basis of design for the project. The SFPE Engineering Guide to Performance Based Fire Protection lists the goals for fire safety in performance-based design as follows [18]:

- **Provide life safety for the public, building occupants, and emergency responders.** Minimize fire-related injuries, and prevent undue loss of life.
- **Protect property.** Minimize damage to property and cultural resources from fire. Protect building, contents, and historical features from fire and exposure to and from adjacent buildings.
- **Provide for continuity of operations.** Protect the organization's ongoing mission, production, or operating capability. Minimize undue loss of operations and business-related revenue due to fire-related damage.
- **Limit the environmental impact of the fire.**

Once the performance criteria are agreed on, a combination of fire models, calculations, and experimental data are used to develop an FPLS design and prove it meets the criteria.

NFPA 502 does include some prescriptive-based design requirements. One example is the Section 9.1.2 requirement that if FFFS are installed, they shall be installed, inspected and maintained per NFPA standards including NFPA 11, NFPA 13, NFPA 15, NFPA 16, NFPA 18, NFPA 18A, NFPA 25 and NFPA 750. NFPA 13 is the standard for installation of sprinkler systems and it is a primarily prescriptive-based standard; for example, water application rate is explicitly defined for different commodities. In contrast, the standard for water mist fire protection, NFPA 750, does not provide an explicit water flow rate requirement.

Design of FPLS systems may also include a risk analysis, which considers the potential hazards to the facility and the associated consequences of those hazards. Risk-based approaches seek to balance safety and resources and can follow the four viewpoints of ethics [19]:

- **Utilitarian test**: design must produce at least as much good for those affected as any alternative design
- **Duty test**: design must satisfy moral, legal, and occupational obligations
- **Rights test**: design must consider the viewpoints of the parties involved (owner, builder, user, etc.)
- **Virtue test**: design is the best option when considering all three above tests

NFPA 502 Section A.4.3.1 suggests additional references to guide risk assessments.

2.4.3 Overview and Application of NFPA 502

NFPA 502 covers road tunnels, bridges, and other limited access highways. The standard sets out minimum requirements for FLS provisions including, but not limited to, ventilation, egress, lighting, electrical (power), signage, traffic control, fire standpipe, FFFS, and incident management plans. To be enforced as a legal requirement, NFPA 502 is normally adopted by the AHJ who has authority over the fire systems, such as the fire marshal, or through a fire code or on a project-by-project basis [12].

NFPA 502 divides tunnels into different categories depending on their length and the volume of traffic. Regardless of the tunnel length, Section 4.3.1 of NFPA 502 lists a variety of factors that must be considered during the engineering analysis of the FPLS design, regardless of the length of the tunnel.

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 considered 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 [12]. The scope and ultimate acceptance of an engineering analysis is determined by the AHJ.

One area where FFFS are more explicitly recognized in NFPA 502 is the demonstration that they 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 requirements:

> 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 fire fighting 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 [19]:

- **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 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, NFPA 25 Standard for the Inspection, Testing and Maintenance of Water-Based Fire Protection Systems, and NFPA 72 National Fire Alarm and Signaling Code.

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

2.4.4 Adoption of NFPA 502

Worldwide, NFPA 502 is adopted in Singapore, with recognition of the standard in Europe, the Middle East, Australia, New Zealand, and Japan. In the U.S., New York, Massachusetts, Florida, and Washington all have legislative adoption of NFPA 502. Many other States and Canadian provinces consistently adopt NFPA 502.

The New York City Fire Code 2014 Edition recognizes road tunnels and specifically cites NFPA 502 2011 Edition [20]. 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.

The City of Seattle Fire Code 2015 Edition recognizes road tunnels and specifically cites NFPA 502 2014 Edition [21]. The Seattle Fire Code requires installation of FFFS in accordance with NFPA 13 Extra Hazards Group 2. The 2019 edition of the code will adopt NFPA 502 2017.

2.4.5 Practitioner Qualifications

Due to the complexities of analyzing fire, designers of FPLS systems must be experienced, and well versed in current research and analysis techniques. The Society of Fire Protection Engineers (SFPE) states that the role of the engineer is to "identify hazards, characterize risk, and design safeguards that aid in preventing, controlling and mitigating the effects of fires" [22]. Per the SFPE a fire protection engineer should have a competency in the four main areas: fire science (heat transfer, fire chemistry, fire dynamics), human behavior and evacuation (physiological response to fire, egress and life safety concepts), fire protection systems (passive, active, detection and alarm, suppression), and fire protection analysis (performance-based design, smoke management, egress analysis, structural fire protection, risk management, computer models, codes and standards). Practitioner qualifications relative to role are given in Table 2-7 (as recommended by authors).

Table 2-7: Typical practitioner qualifications.

Qualification	Designer	Design lead	Technical reviewer
Education	Bachelor's degree (mechanical or fire protection focus)	Bachelor's degree (mechanical or fire protection focus)	Bachelor's degree (mechanical or fire protection focus)
Experience	5 years	10 years	15 years
Skills	Competency with fire science, fire protection systems and analysis, and evacuation Familiar with recent research	Command of fire science, fire protection systems and analysis, and evacuation Knowledgeable about recent research Understanding of coordination requirements with other disciplines (structural, electrical, etc.)	Command of fire science, fire protection systems and analysis, and evacuation Knowledgeable about recent research Understanding of coordination requirements with other disciplines (structural, electrical, etc.)
Licensing	Not applicable	Professional engineering license	Professional engineering license
Other	Not applicable	Regularly publishes technical papers Contributes to technical committees	Regularly publishes technical papers Contributes to technical committees

2.4.6 Role of Stakeholders

The process of determining FPLS requirements starts with the development of codes and standards. Technical committees are staffed by design engineers, fire marshals, end users, industry subject matter experts, first responders, manufacturers, and researchers. Participants in technical committees tends to be on a voluntary basis, with employed staff assisting with the implementation of modifications to a standard, code, etc. These groups have the responsibility of incorporating the latest research and best practices into the codes and standards. The code/standard then provides users with an accepted guide to approaching FPLS systems and a means of judging the appropriateness of the design.

Before the design of a tunnel FPLS system begins, the relevant stakeholders must meet to determine the FPLS system performance objectives, and establish the FPLS criteria. This primarily involves the tunnel owner, operator, state and local emergency response agencies, and the AHJ. Key operational issues that they must consider include: the type of vehicles expected to use the tunnel, if the tunnel is a designated HAZMAT route, and the level of risk a fire incident would bring to tunnel users and surrounding communities. Elected officials and the public may also contribute to these operational policies.

The agency that has the role of AHJ is often the local fire department or fire marshal's office. The role may be filled by multiple individuals or agencies depending on the capabilities of the reviewers (i.e. technical versus operational experience).

During these meetings and continuing through the tunnel design process, agencies and first responders will focus on the emergency response and safety aspects of the tunnel. The design should be tailored to work with the emergency response plans and procedures defined by the local fire department and other emergency responders. A list identifying the major priorities of each stakeholder is given in Table 2-8 (developed by authors using prior project experience).

Table 2-8: Main stakeholder priorities (typical).

Entity	Public safety	Emergency response	Structural protection	Asset resiliency	Facility robustness	Infrastructure sustainability	Disaster recovery	Highway system reliability	Cost savings
Tunnel owners	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
State and local agencies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
AHJs	Yes	Yes	Yes	No	Yes	No	No	No	No
Technical committee members	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
FPLS designers and researchers	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Fire marshals and fire departments	Yes	Yes	Yes	No	Yes	No	Yes	No	No
Elected officials	Yes	No	No	No	No	Yes	Yes	Yes	Yes
Public	Yes	No	No	No	No	Yes	Yes	Yes	Yes

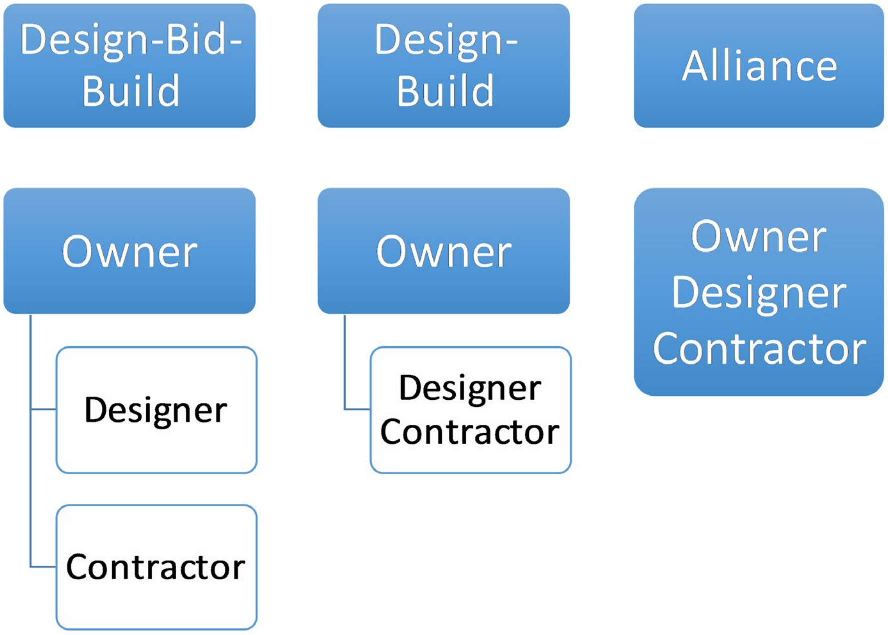
2.4.7 Project Delivery

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.

One method of project delivery used in New Zealand is 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 2-5 provides a schematic that contrasts alliance project delivery with design-bid-build and design-build project delivery [15].

Construction methods such as construction manager / general contractor (CMGC) are like a design-build method and are aimed at achieving improved collaboration between the design and construction phases [23]. For complex projects, such as retrofitting an FFFS, these alternative delivery methods offer potential risk mitigations and improved project outcomes.

For any project delivery method, due to complexity and interaction of FPLS systems with other systems, the use of a concept of design for purposes of budgeting and bidding is not recommended, unless the concept includes details on how the FPLS system will be used and explicit minimum requirements (such as water application rate and FFFS type). This usually involves far more detail than is normal with a concept of design. If a design-build method is used, then the concept of design without detailed provisions for minimum requirements for FPLS places the burden of correctly installing these complex systems on potentially very inexperienced contractors. This can place the AHJ in difficult position when detail designs are developed as they potentially will not meet the requirements. One way to mitigate this issue is to ask designers and contractors to have a demonstrable track record in highway tunnel FPLS, particularly with respect to EVS and FFFS.



Source: FHWA

Figure 2-5: Project delivery methods [15]

2.5 FFFS in U.S. Tunnels

Over the past 10 to 15 years, FFFS have become more prevalent in U.S. highway tunnels. FFFS have been used to mitigate risk in higher hazard scenarios, including larger design fires and urban tunnels/overbuilds. FFFS have also been investigated for use in retrofits to increase the FHRR an existing tunnel can manage, bringing the tunnel more in line with existing standards. FFFS might be able to be used in existing tunnels with undersized mechanical ventilation to reduce or limit the FHRR, thereby allowing the existing tunnel EVS to manage smoke; this might be a cost-effective way to provide an improved level of safety.

A selection of U.S. tunnels and FPLS related parameters is given in Table 2-9.

2.6 Summary

Questions raised in the introduction are outlined below, along with comments on the findings of the literature survey and synthesis.

- ***What types of tunnels are constructed and how?***
  The four main tunnel types are circular, rectangular, horseshoe, and oval. They are constructed by boring, blasting, excavating, or by sinking a precast tube.
- ***What are the principal functional systems?***
  The principal functional systems include EVS, FFFS, CCTV, public address and communications, signage, lighting, standpipe, SCADA, PA, power, and drainage.
- ***What are the U.S. FLS approaches for highway tunnels?***
  The primary FLS approach for highway tunnels is compliance with NFPA 502 via an engineering analysis showing the FLS goals are met. For longer tunnels, this usually includes an EVS at a minimum.

- ***Where do FFFS fit into the overall FLS picture for a U.S. highway tunnel?***
  For tunnels complying with NFPA 502, FFFS should be considered as part of the overall FLS design. Historically, FFFS have had limited use in U.S. tunnels, but they are becoming more common in line with international practices.
- ***How does the tunnel construction affect the FPLS system?***
  The tunnel construction will greatly affect the FPLS systems and their installation. For example, a transverse ventilation system cannot be used unless separate air ducts are part of the tunnel construction. FFFS and other systems are less affected by construction type. However, routing of pipework and other elements requires sufficient clearance above the roadway, space for ancillary equipment must be considered, along with supporting infrastructure to supply/remove water from the FFFS.

Table 2-9: Selected US tunnels with longitudinal ventilation.

Tunnel / location	Year opened	Length	Type	Traffic	Rehab	Ventilation	FFFS / water application	Urban or rural
Anton Anderson Alaska	2000	13,727 ft (4184 m)	1 bore	1 lane, 1 bore, combined rail/road	Not applicable	Longitudinal	Not applicable	Rural
Central Artery - I90 Extension, Boston, Massachusetts	2003	5,300 ft (1,615 m)	4 bores	4 bores, 7 lanes	Not applicable	Transverse with longitudinal on some ramps	Not applicable	Urban
Central Artery-I93, Boston, Massachusetts	2003	8,100 ft (2,469 m)	2 bores	2 bores, 6 lanes	Not applicable	Transverse with longitudinal on some ramps	Not applicable	Urban
Cumberland Gap, Kentucky – Tennessee	1996	4,600 ft (1,402 m)	2 bores	2 bores, 4 lanes	Not applicable	Longitudinal	Not applicable	Rural
C70 Cover, Denver, CO	U/C	1,000 ft (300 m)	2 bores, cut and cover	2 bores, 12 lanes	Not applicable	Longitudinal	Deluge 0.15 gpm/ ft^2 (6 mm/min)	Urban
Doyle Drive Tunnels, San Francisco, CA	2015	750-1030 ft (229-314 m)	4 bores	Unidirectional, 3/4 lanes per bore, 65 mph (105 kmh)	Not applicable	Longitudinal, jet fans	Deluge 0.20 gpm/ft^2 (8 mm/min)	Urban
East End Tunnel, Louisville, KY	2016	2,000 ft (610 m)	2 bores	Unidirectional, 2 lanes per bore	Not applicable	Longitudinal, jet fans	Deluge	Not applicable
Elizabeth River – Midtown, Norfolk – Portsmouth, Virginia	1962	4,194 ft (1,278 m)	1 bore, subaqueous	1 bore, 2 lanes	2015	Longitudinal, transverse prior to 2015 rehab	Not applicable	Urban
Elizabeth River – Downtown, Norfolk – Portsmouth, Virginia	1954 / 1986	3,350 ft (1,021 m) 3,814 ft (1,163 m)	2 bore, subaqueous	2 lanes each direction	2015	Longitudinal, transverse prior to 2015 rehab	Not applicable	Urban

Tunnel / location	Year opened	Length	Type	Traffic	Rehab	Ventilation	FFFS / water application	Urban or rural
Liberty, Pittsburgh, Pennsylvania	1924	5,905 ft (1,800 m)	2 bores, bored	2 bores, 4 tunnels	Not applicable	Longitudinal	Not applicable	Rural
Midtown Tunnel, Norfolk, VA, (new tunnel only)	2016	4,054 ft (1,236 m)	2 bores	Unidirectional, 2 lanes per bore, AADT: 40000, 35 mph (56 kmh)	Not applicable	Longitudinal, jet fans	Deluge 0.15 gpm/ft^2 (6 mm/min) (new tunnel)	Urban
Port of Miami Tunnel, Miami, FL	2014	4,200 ft (1,280 m)	2 bores	Unidirectional, 2 lanes per bore, AADT: 7000, 35 mph (56 kmh)	Not applicable	Longitudinal, jet fans	Deluge 0.20 gpm/ft^2 (8 mm/min)	Urban
Wawona, California	1933	4,233 ft (1,291 m)	1 bore, bored	1 bore, 2 lanes	Not applicable	Longitudinal	Not applicable	Rural
West Rock (Heroes Tunnel), New Haven, Connecticut	1949	1,200 ft (366 m)	2 bores, bored	2 bore, 4 lanes	Not applicable	Longitudinal	Not applicable	Rural
Wheeling, West Virginia	1967	1,519 ft (463 m)	2 bores, bored	2 bores, 4 lanes	Not applicable	Longitudinal	Not applicable	Rural

Table 2-10: Selected US tunnels with transverse or semi-transverse ventilation.

Tunnel / location	Year opened	Length	Type	Traffic	Rehab	Ventilation	FFFS / water application	Urban or rural
Alaska Way Tunnel, Seattle, WA	2019	9,800 ft (2,988 m)	1 bore	Unidirectional, bi-level bore, 4 lanes per bore, 50 mph (80 kmh)	Not applicable	Semi-transverse, jet fans and exhaust duct with point exhaust	Deluge 0.30 gpm/ft^2 (12 mm/min)	Urban
Allegheny, Pennsylvania	1940 1966	6,703 ft (1,851 m)	2 bores, bored	2 bores, 4 lanes	Not applicable	Semi-transverse	Not applicable	Rural
Baltimore Harbor Tunnel, Baltimore, MD	1957	7650 ft (2,332 m)	2 bores, subaqueous	Unidirectional, 2 lanes per bore, AADT: 75616, 50 mph	Not applicable	Transverse	Not applicable	Urban
Bankhead, Mobile, Alabama	1941	3,109 ft (948 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Semi-transverse	Not applicable	Rural
Big Walker, Virginia	1972	4,229 ft (1,289 m)	2 bores, bored	2 bores, 4 lanes	Not applicable	Transverse	Not applicable	Rural
Blue Mountain, Pennsylvania	1940	4,340 ft (1,323 m)	2 bores, bored	2 bores, 4 lanes	Not applicable	Semi-transverse	Not applicable	Rural
Brooklyn Battery, New York, NY	1950	9,210 ft (2,807 m)	2 bores, subaqueous	2 bores, 4 lanes	Not applicable	Transverse	Not applicable	Urban
Caldecott, Oakland, California	1937 (2 bores) 1964 (third bore) 2013 (fourth bore)	3,350 ft (1,021 m)	4 bores	4 bores, 8 lanes	Not applicable	Transverse (original three bores) Longitudinal (bore four)	Not applicable	Urban
Callahan, Boston, Massachusetts	1961	5,085 ft (1,550 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Transverse	Not applicable	Urban

Tunnel / location	Year opened	Length	Type	Traffic	Rehab	Ventilation	FFFS / water application	Urban or rural
Central Artery-I90 Extension, Boston, Massachusetts	2003	5,300 ft (1,615 m)	4 bores	4 bores, 7 lanes	Not applicable	Transverse with longitudinal on some ramps	Not applicable	Urban
Central Artery-I93, Boston, Massachusetts	2003	8,100 ft (2,469 m)	2 bores	2 bores, 6 lanes	Not applicable	Transverse with longitudinal on some ramps	Not applicable	Urban
Chesapeake Bay – Thimble Shoal, Norfolk, Virginia	1964	5,740 ft (1,750 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Transverse	Not applicable	Rural
Chesapeake Bay – Baltimore Channel, Norfolk, Virginia	1961	5,450 ft (1,661 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Transverse	Not applicable	Rural
Detroit Windsor, Michigan – Ontario	1930	5,125 ft (1,562 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Transverse	Not applicable	Urban
East River, Virginia – West Virginia	1974	5,661 ft (1,726 m)	2 bores, bored	2 bores, 4 lanes	Not applicable	Transverse	Not applicable	Rural
Eisenhower-Johnson Memorial Tunnel, Dillon, CO	1979	8,940 ft (2,726 m)	2 bores	Unidirectional, 2 lanes per bore, AADT: 34000, 50 mph (80 kmh)	FFFS installed 2016	Transverse	Deluge 0.16 gpm/ft^2 (6.5 mm/min)	Rural
Fort McHenry Tunnel, Baltimore, MD	1985	7920 ft (2,414 m)	4 bores, subaqueous	Unidirectional, 2 lanes per bore, AADT: 115000, 55 mph	Not applicable	Transverse	Not applicable	Urban
Fort Pitt, Pennsylvania	1960	3,603 ft (1,098 m)	2 bores	2 bores, 4 lanes	Not applicable	Semi-transverse	Not applicable	Rural

Tunnel / location	Year opened	Length	Type	Traffic	Rehab	Ventilation	FFFS / water application	Urban or rural
Hampton Roads, Hampton – Norfolk, Virginia	1958 1975	7,470 ft (2,277 m) 7,314 ft (2,229 m)	2 bores, subaqueous	2 bores, 4 lanes	Not applicable	Transverse	Not applicable	Urban (seasonal)
Harano, O'ahu, Hawaii	1997	5,165 ft (1,574 m) 4,890 ft (1,491 m)	2 bores	2 bores, 4 lanes	Not applicable	Transverse	Not applicable	Rural
Holland Tunnel, New York, NY	1927	8,558 ft (2552 m)	2 bores	Unidirectional, 2 lanes per bore, AADT: 89,792, 35 mph	2003, improve New York exit plaza	Transverse	Not applicable	Urban
Kittatinny, Pennsylvania	1940 1968	4,728 ft (1,441 m)	2 bores, bored	2 bores, 4 lanes	Not applicable	Semi-transverse	Not applicable	Rural
Lehigh (1940 tunnel), Pennsylvania	1940	4,462 ft (1,360 m)	2 bores,	2 bores, 4 lanes	Not applicable	Semi-transverse	Not applicable	Rural
Lincoln Tunnel, New York, NY	1937	8,216 ft (2,504 m)	3 bores, subaqueous	Unidirectional, 2 lanes per bore, AADT: 112995, 35 mph	Repaving in 1989	Transverse	Not applicable	Urban
Lowry Hill, Minneapolis, Minnesota	1971	1,496 ft (456 m)	3 bores	3 bores, 6 lanes	Not applicable	Semi-transverse	Not applicable	Urban
Mall, DC	1973	3,400 ft (1,036 m)	2 bores	2 bores, 8 lanes	Not applicable	Transverse	Not applicable	Urban
Memorial Tunnel (West Virginia Turnpike), West Virginia	1954	2,780 ft (848 m)	1 bore, bored	1 bore, 2 lanes	Not applicable	Transverse	Not applicable	Rural
Mercer Island, Washington	1999	2,999 ft (914 m)	3 bores	3 bores, 8 lanes	Not applicable	Transverse	Not applicable	Urban

Tunnel / location	Year opened	Length	Type	Traffic	Rehab	Ventilation	FFFS / water application	Urban or rural
Mobile River, Mobile, Alabama	1972	3,000 ft (915 m)	2 bores	2 bore, 2 lanes	Not applicable	Semi-transverse	Not applicable	Urban
Monitor Merrimac, Virginia	1992	4,783 ft (1,458 m)	2 bores, subaqueous	2 bores, 4 lanes	Not applicable	Transverse	Not applicable	Rural
Mount Baker Ridge, Seattle, Washington	1989	3,501 ft (1,067 m)	3 bores	3 bores, 8 lanes	Not applicable	Transverse	Not applicable	Urban
Posey, Oakland, California	1928	3,545 ft (1,081 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Transverse	Not applicable	Urban
Squirrel Hill, Pennsylvania	1953	4,225 ft (1,288 m)	2 bores	2 bores, 4 lanes	Not applicable	Semi-transverse	Not applicable	Rural
Sumner, Boston, Massachusetts	1934	5,657 ft (1,724 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Transverse	Not applicable	Urban
Ted Williams, Boston, Massachusetts	1995	8,957 ft (2,730 m)	2 bores, subaqueous	2 bores, 4 lanes	Not applicable	Transverse	Not applicable	Urban
Tuscarora, Pennsylvania	1940 and 1968	5,328 ft (1,624 m)	2 bores	2 bores, 4 lanes	Not applicable	Semi-transverse	Not applicable	Rural
Queens Midtown Tunnel, New York, NY	1940	6,414 ft (1,955 m)	2 bores, subaqueous	Unidirectional, 2 lanes per bore, AADT: 73470, 35 mph (56 kmh)	Not applicable	Transverse	Not applicable	Urban
Washburn, Houston, Texas	1950	2,936 ft (895 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Semi-transverse	Not applicable	Urban
Webster Street, Oakland, California	1963	3,350 ft (1,021 m)	1 bore, subaqueous	1 bore, 2 lanes	Not applicable	Transverse	Not applicable	Urban
Wilson, O’ahu, Hawaii	1960	2,813 ft (857 m) 2,775 ft (846 m)	2 bores	2 bores, 4 lanes	Not applicable	Semi-transverse	Not applicable	Rural

Table 2-11: Selected US tunnels with natural ventilation.

Tunnel / location	Year opened	Length	Type	Traffic	Rehab	Ventilation	FFFS / water application	Urban or rural
Green River, Wyoming	1966	1,135 ft (346 m)	2 bores, bored	2 bores, 4 lanes	Not applicable	Natural	Not applicable	Rural
Pali, O’ahu, Hawaii	1961 1957	1,577 ft (481 m) 1,500 ft (457 m)	2 bores	2 bores, 4 lanes	Not applicable	Natural	Not applicable	Rural

3 TUNNEL DESIGN FIRES

A design fire scenario is "an idealization of a real fire occurrence" [24]. The design fire is important because it forms a major part of the basis of the design for FPLS systems. Design features that are directly impacted include egress, ventilation, structural fire resistance, FFFS, and fire fighting strategy. NFPA 502 Section 11.4.2 [12] states that the "design of the emergency ventilation system shall be based on a fire scenario having defined heat release rates, smoke release rates, and carbon monoxide release rates, all varying as a function of time." Development of the design fire scenario requires, per NFPA 502 Section 11.4.2, consideration of "the operational risks that are associated with the types of vehicles expected to use the tunnel."

The topic of tunnel design fires is covered in this chapter. Special topics include fire terms and dynamics, tunnel specifics, previous incidents and tests, standards, and FFFS.

3.1 Tunnel Fire Studies and Reviews

Several studies and reviews of tunnel fires have been conducted previously. The material in this chapter has been developed based on these references. These sources should be consulted for more detailed data and analysis. A review of the main documents follows below:

- **Design Fires in Road Tunnels, National Cooperative Highway Research Program (NCHRP) Synthesis 415** [24]: This report provides a comprehensive review of the design fire topic as well as consideration of design factors and impacts. Topics include: tunnel safety projects, tenability, fire incidents and testing, analytical fire modeling, design guidance and standards, and impact of FFFS. The report was developed as a part of the U.S. National Cooperative Highway Research Program.
- **Tunnel Fire Dynamics** [10]: This textbook was first published in 2015 and is authored by research staff from the Swedish group RISE. The text covers the subject of tunnel fires specifically. It is mostly focused on theory but within the chapters there is a substantial compilation of data related to design fires. Topics include: fuel and ventilation controlled fires, fire tests, fire growth and heat release rates, combustion products, temperatures and heat flux, fire spread, visibility and tenability, fire suppression, fire detection, and CFD modeling.
- **Design Fire Characteristics for Road Tunnels, Technical Committee 3.3 Road Tunnels Operations, World Road Association (PIARC)** [25]: This report looks at design fires in road tunnels and recommends design fire curves for various vehicles. A review of design fire approaches in different countries is provided, along with test data and experiences from previous incidents.
- **Handbook of Tunnel Fire Safety** [26]: Chapter 14 of this handbook provides a summary of heat release rates in tunnel fires. Experimental data are provided for sedan vehicles, buses, and heavy goods vehicles (HGVs).
- **Fires in Transport Tunnels, Report on Full-Scale Tests (Eureka Tunnel)** [27]**:** The Eureka Tunnel project was a cooperative effort between European countries in the 1990s. Full-scale fire tests were performed using single sedan vehicles, a public bus, a heavy goods vehicle, a subway car, and a commuter rail car. Measurements of fire heat release rate, soot concentration, carbon monoxide concentration, and tunnel temperatures were reported.

- **Memorial Tunnel Fire Ventilation Test Program, Comprehensive Test Report** [28]**:** This study was focused on ventilation systems for smoke management. Systems investigated included full transverse ventilation, partial transverse ventilation, single point extraction, longitudinal ventilation, and natural ventilation. Although the study did not pertain directly to the design fire determination, it considered the ability of ventilation systems to manage smoke from a known fire heat release rate.
- **Recommended AASHTO Guidelines for Emergency Ventilation Smoke Control in Roadway Tunnels** [29]**:** Following from earlier design fire reviews, this document looks at the ventilation system design and details an approach to design. It also considers fire detection and emergency ventilation controls.
- **SFPE Handbook of Fire Protection Engineering** [30]: This reference contains a compilation of material properties with respect to fire, including: heat of combustion, soot yield, carbon monoxide yield, and the chemical formula. It serves as a useful reference for defining detailed fire properties.

3.2 Fire Terms and Dynamics

A design fire is defined as "an idealization of a real fire occurrence" [24]. Fire is defined by NFPA 921 as "a rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities" [31].

A simplified and typical chemical reaction (for methane) associated with fire is provided in Figure 3-1. For this reaction to occur, sufficient heat, fuel and oxygen are needed. An interruption to one of the three key components of the fire chemical reaction will affect the burning behavior of the material.

$$FUEL + OXYGEN \rightarrow PRODUCTS$$

$$CH_4 + 2(3.76N_2 + O_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

Figure 3-1: Equation. Typical fire chemical reactions.

NFPA provides several definitions related to the design fire, which will be adopted herein:

- **Effective heat of combustion.** The measured heat release divided by the mass loss for a specified time period (from NFPA 289).
- **Fire control.** Limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage (from NFPA 13).
- **Fire growth rate.** Rate of change of the heat release rate. Some factors that affect the fire growth rate are exposure, geometry, flame spread, and fire barriers (from NFPA 130).
- **Fire hazard.** Any situation, process, material, or condition that can cause a fire or explosion or that can provide a ready fuel supply to augment the spread or intensity of a fire or explosion, all of which pose a threat to life or property (from NFPA 921).

- **Fire heat release rate.** (FHRR) Rate of energy release for a given fire scenario or fire test, expressed as a function of time (from NFPA 130).
- **Fire profile.** For a given fire scenario, the fire carbon monoxide, heat release, and smoke and soot release rates expressed as a function of time (from NFPA 130).
- **Fire scenario.** A set of conditions that defines the development of a fire, the spread of combustion products in a fixed guideway transit or passenger rail system, the reaction of people to the fire, and the effects of the products of combustion (from NFPA 130).
- **Fire soot release rate.** Rate of soot release for a given fire scenario expressed as a function of time (from NFPA 130).
- **Fire spread.** The movement of fire from one place to another (from NFPA 921).
- **Fire suppression.** Sharply reducing the heat release rate of a fire and preventing its regrowth by means of direct and sufficient application of water through the fire plume to the burning fuel surface (from NFPA 502).
- **Smoke.** The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass (from NFPA 130).
- **Soot yield.** The mass (weight) of soot emitted per mass (weight) of the fuel consumed: g (oz) of soot emitted per g (oz) of fuel burned (from NFPA 130).
- **Soot.** Black particles of carbon produced in a flame (from NFPA 921).
- **Pyrolysis.** A process in which material is decomposed, or broken down, into simpler molecular compounds by the effects of heat alone; pyrolysis often precedes combustion (from NFPA 921).
- **Total fire load.** The total heat energy (in Joules or Btu) of all combustibles available from the constituent materials of a certain fuel package (from NFPA 130).

Most tunnel fires involve solid phase burning where the solid fuel undergoes pyrolysis based on the heat flux to the surface and the material properties/arrangement. The amount of fuel burned and the fire heat release rate depend on the heat feedback to the fuel. Definition of a design fire involves, at a minimum, specification of the following:

- Heat release rate as a function of time (refer to Figure 3-2).
- Effective heat of combustion.
- Soot and other combustion product yields.
- Radiative and chemical heat fractions.

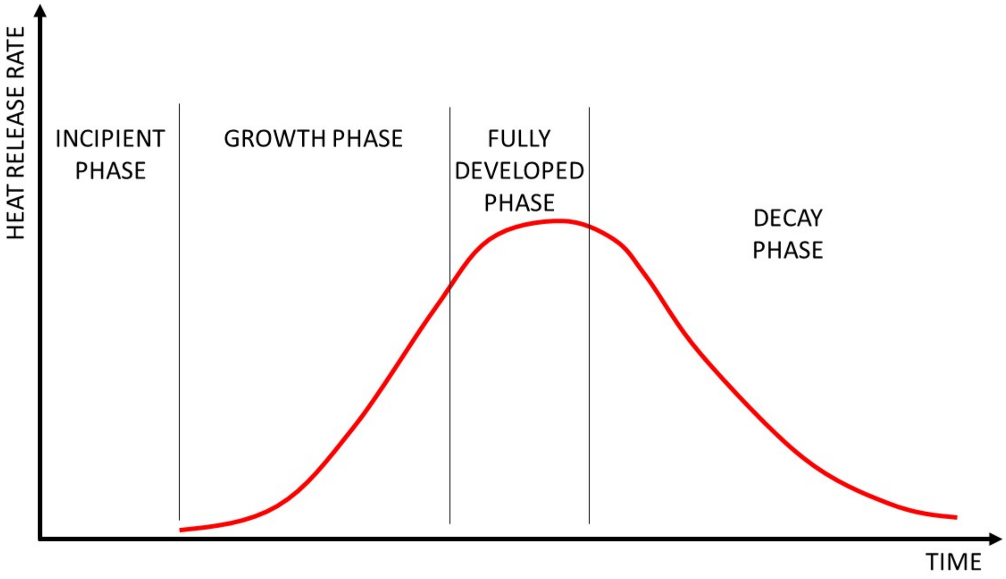


Figure 3-2: Graph. Typical design fire heat release rate profile [1].

3.3 Fires in Highway Tunnels

The enclosed environment of a tunnel presents more risk than an open area fire:

- Heat feedback to the fire is increased in the enclosed environment; heat from the fire is constrained to the tunnel and the lining temperature increases [10]. These factors cause an enhancement in the fire growth rate through increased heat flux to the exposed combustible surfaces.
- Ventilation affects the availability of oxygen for combustion and smoke propagation. Fires can be fuel-controlled or ventilation-controlled (i.e. amount of oxygen available is limited). The fuel-controlled fire undergoes complete combustion as enough oxygen reaches the fire. The ventilation-controlled fire does not receive enough oxygen, producing increased amounts of toxic products or becoming starved of oxygen by recirculated air [10]. In addition to this, sloped tunnels act as a chimney for smoke, making smoke management (emergency ventilation system) a critical life safety provision.

3.3.1 Fire Dynamics in Tunnels

Unique factors for fire dynamics that are introduced by the tunnel environment include the geometry (width, height, aspect ratio, blockage ratio), ventilation rate and potential for fire spread.

A practical example of fire spread risk is seen in the Mont Blanc Tunnel fire where the fire spread to 23 heavy goods vehicles, a small truck, one motorcycle, and nine cars [10]. Over 2952 ft. (900 m) of tunnel were damaged by the fire.

Statistical analysis of experiment data was applied to understand the impact of tunnel geometry on the FHRR [32]. The data considered a tunnel environment versus the open environment. In general, the data showed an enhancement in the FHRR due to geometry. The conclusion was made that under certain conditions a naturally ventilated fire in a tunnel could have a peak FHRR up to four times greater than a fire in the open air. It was found that tunnel width had the most significant effect on FHRR compared with other factors such as aspect ratio, height, and blockage ratio. The relationship is provided in Figure 3-3. This equation is based on limited data and probably only valid in certain circumstances, and other researchers have found conflicting results.

Work by other researchers, which included experiments in scale models, found that tunnel height had more of an influence on FHRR, and it was noted that other factors, including shape and position of the flame, plus air flow patterns, were also likely to have an affect [33] [24]. This difference illustrates that expressions such as those given in Figure 3-3 are probably overly simplistic and do not capture all aspects of fire dynamics (heat feedback, ventilation) well enough, and that such equations are of limited practical use thus.

$$Q_{add} = 24Q_{open}\left(\frac{W_f}{W_t}\right)^3$$

$$Q_{tun} = Q_{open} + Q_{add}$$

Figure 3-3: Equation. FHRR enhancement due to tunnel width effects [32].

In Figure 3-3 symbols are as follows: Q_{add} is the additional fire heat release due to width effects (W), Q_{open} is the fire heat release in the open environment (W), W_f is the width of fire object (m), W_t is the width of tunnel (m), and Q_{tun} is the fire heat release in the tunnel (W).

Further work on the influence of ventilation on FHRR included experiments in scale models, which concluded that velocities around 1.6 m/s to 4.3 m/s will create a peak FHRR 1.3 to 1.7 times the value measured for a fire outside the tunnel. Fire growth rate was found to increase with longitudinal velocity in a linear fashion [34]. Scale tests showed that the fire growth rate was nearly three times larger than a free burn when the ventilation velocity was equivalent to 4.3 m/s in full-scale.

Influence of ventilation on FHRR is linked to fire spread. Fire spread can occur via flame impingement, flame spread, remote ignition (due to heat flux), fuel transfer, or explosion [24]. Various criteria have been applied to determine flame spread. A review of work looking at flame spread with wood cribs concluded that fire would spread to a neighboring wood crib if the gas layer temperature is 600°C or greater [35]. This work was conducted in a scale model and caution must be exercised in generalizing conclusions; that said, the tests showed a critical heat flux value for ignition downstream of the fire as follows [35]:

- Minimum critical heat flux of 20 kW/m^2 for wood and plastic fuels.
- For a natural ventilation scenario, the critical heat flux was 12.5 kW/m^2. The heat flux was most likely reduced due to the reduced convective heat loss from the solid material at lower air speeds.

- Plastic fuel targets downstream of the fire exhibited different burning behavior to the wood targets. Significant amounts of vaporized gases were produced by the plastic materials but at high ventilation velocities these were blown away before ignition.
- Fire spread upstream is less of a concern in a longitudinally ventilated tunnel. In the scale model tests, upstream fire spread was only observed for tests where the tunnel was naturally ventilated, or when the upstream velocity was much less than the critical velocity to manage backlayering.

In summary, ventilation can have a significant impact on the fire growth rate and peak FHRR. The geometry is also important, with narrower tunnels tending to enhance heat feedback and peak FHRR.

3.3.2 Fire Incidents in Tunnels

Fire incidents are thoroughly documented in the literature referenced in Section 3.1. A list of road tunnel fires from the NCHRP synthesis Design Fires in Road Tunnels [24] is reproduced in Table 3-1. Key points include the following:

- Heavy goods vehicle fires are more serious events in terms of life safety and tunnel damage consequences (see Mont Blanc (1999) and Tauern (1999) incidents).
- Car fires tend to be less serious, however, the smoke and heat from a car fire can still cause damage and disruption.

Later sections in this review consider the impact of FFFS on the fire events and make contrast to comparable incidents in tunnels without FFFS.

Statistics on fire frequency and consequences are useful metrics to consider when designing tunnel FLS provisions. Statistics on fires in tunnels are relatively sparse since fires tend to be rare events. For instance, in French tunnels published data indicate fire rates per 100 million vehicle miles of: 1.6 to 3.2 passenger car fires, 12.9 truck fires of any importance, 1.6 truck fires with some damage to the tunnel and 0.16 to 0.48 serious truck fires [24].

3.3.3 Hazardous Vehicle Fire Incidents in Tunnels

Hazardous material transport through tunnels is regulated by the US DOT, and is often banned in tunnels. Information on hazardous materials is available through the Federal Motor Carrier Safety Administration (FMCSA) [36]. Hazardous cargo can include (but is not limited to) explosives, gases, flammable liquids and solids, water reactive substances, oxidizing substances, poisonous or infectious substances, radioactive material, and corrosives. Tunnel operations personnel and designers should be aware of the potential for transport of these materials through a facility. Detailed coverage of all materials is beyond the scope of this document; however, some discussion of tanker and liquid fuel spill fires is provided herein.

Tanker fires are very rare events with potentially major consequences:

- The 1982 Caldecott tunnel fire involved a gasoline tanker carrying 8,800 gallons, which burned within 40 min, with an average burning rate of 430 MW [37]. There were seven fatalities due to this incident, six vehicles destroyed, superficial damage occurred to the tunnel walls, ceiling and roadway, and most tunnel systems (lighting, signs, alarms, wiring) were destroyed [38].

- A tanker fire on the I5 interchange in California shut down parts of the tunnel for 5 months in 2013. The tanker was carrying an estimated 8,500 gallons of gasoline, and the repairs cost an estimated $16.5 million [39].
- A tanker fire occurred in the Skatestraum Tunnel in Norway during 2015. The fire involved a tanker holding 16,500 liters of gasoline [40]. The tanker broke off from the main towing truck, causing it to impact the tunnel wall and leak fuel. The fuel spill was most likely ignited by heat from another vehicle. The tunnel grade was 10% and fuel quickly spread down to the tunnel low point and throughout the drainage system. The fire spread over the 900 m length both in the tunnel space and through the drainage system. The peak FHRR was estimated to exceed 400 MW. The FHRR was estimated to exceed 200 MW within two minutes of ignition. Temperature above the burning trailer was estimated at 1350°C. There were no injuries or loss of life, due to quick actions of the truck driver and other vehicle occupants.

Table 3-1: Summary of selected significant road tunnel fire incidents [24].

Location and date	Tunnel length ft. (m)	Significance
Nihonzaka Tunnel, Japan, 1979	6,700 (2,045)	Fire burned for 159 h, 7 dead and 2 injured, multiple vehicles destroyed, structure damaged
Caldecott Tunnel, United States, 1982	3,372 (1,028)	Gasoline tanker fire, 7 dead and 2 injured, 3 trucks and 1 bus and 4 cars damaged/destroyed, structure damaged
Mont Blanc Tunnel, France/Italy, 1999	38,000 (11,600)	Fire for 2+ days, 39 dead, vehicles damaged/destroyed included 23 trucks, 10 cars, 1 motorcycle, and 2 fire engines, tunnel closed for 3 years
Tauern Tunnel, Austria, 1999	21,000 (6,401)	15 h fire duration, 12 dead and 49 injured, 14 trucks and 26 cars destroyed, serious tunnel damage (closed for 3 months)
St. Gottard Tunnel, Switzerland, 2001	55,540 (16,900)	Fire for over 2 days, 11 dead, 2 trucks and 23 vehicles destroyed
Baregg Tunnel, Switzerland, 2003	4,560 (1,390)	2 dead and 21 injured, 4 trucks and 3 fire engines destroyed
Frejus Tunnel, France/Italy, 2005	42,323 (12,900)	6 h duration fire, 2 dead and 21 treated for smoke inhalation, 4 HGV and 3 fire fighting vehicles damaged/destroyed, serious damage to tunnel
Burnley Tunnel, Australia, 2007	9,514 (2900)	3 dead, 4 HGVs and 7 cars damaged, minor structural damage, FFFS prevented a more serious incident
Santa Clarita I-5 Tunnel, United States, 2007	544 (165)	3 dead and 23 injured, 33 tractor/semi-trailer and 1 car damaged/destroyed

3.3.4 Vehicle Fires and Tests

The primary fire load in a tunnel fire is the vehicles. NFPA 502 provides some requirements on design FHRR based on vehicle type. Section 11.4.2 states "the selection of the design fire size heat release rate shall consider the types of vehicles that are expected to use the tunnel." NFPA 502 does not specify what fire size should be used, instead leaving it as a joint decision between the AHJ, designer, and owner. Table A.11.4.1 from NFPA 502 gives suggested heat release rates for common vehicle sizes:

- Passenger car: 5-10 MW (representative FHRR 5 MW)
- Several passenger cars: 10-20 MW (representative FHRR 15 MW) (with FFFS 10-15 MW)
- Bus: 25-34 MW (representative FHRR 30 MW) (with FFFS 20 MW)
- Heavy goods truck: 20-200 MW (representative FHRR 150 MW) (with FFFS 15-90 MW)
- Flammable liquid tanker: 200-300 MW (representative FHRR 300 MW)

There have been several fire tests conducted over the past decades to determine the fire profiles for vehicles [26]. Testing has included single vehicles, multiple vehicles, buses and mock-ups of heavy goods vehicle loads. Tests have been conducted in tunnels and in laboratory configurations. Sample test data are provided as follows:

- Single passenger cars (refer to Figure 3-4)
- Buses (refer to Figure 3-5)
- Heavy goods vehicles (refer to Figure 3-6)

Dangerous goods vehicles are banned in most tunnels, especially in high risk (urban) areas. On that basis, heavy goods vehicle fires are typically most concerning for purposes of tunnel EVS design, since these vehicles have the largest peak FHRRs. In the Eureka test (Figure 3-6) the fuel load was an actual heavy goods vehicle (cab plus trailer with furniture), while the Runehamar test was based on a mock-up vehicle load (wood and plastic pallets, rubber tires, plastic cups).

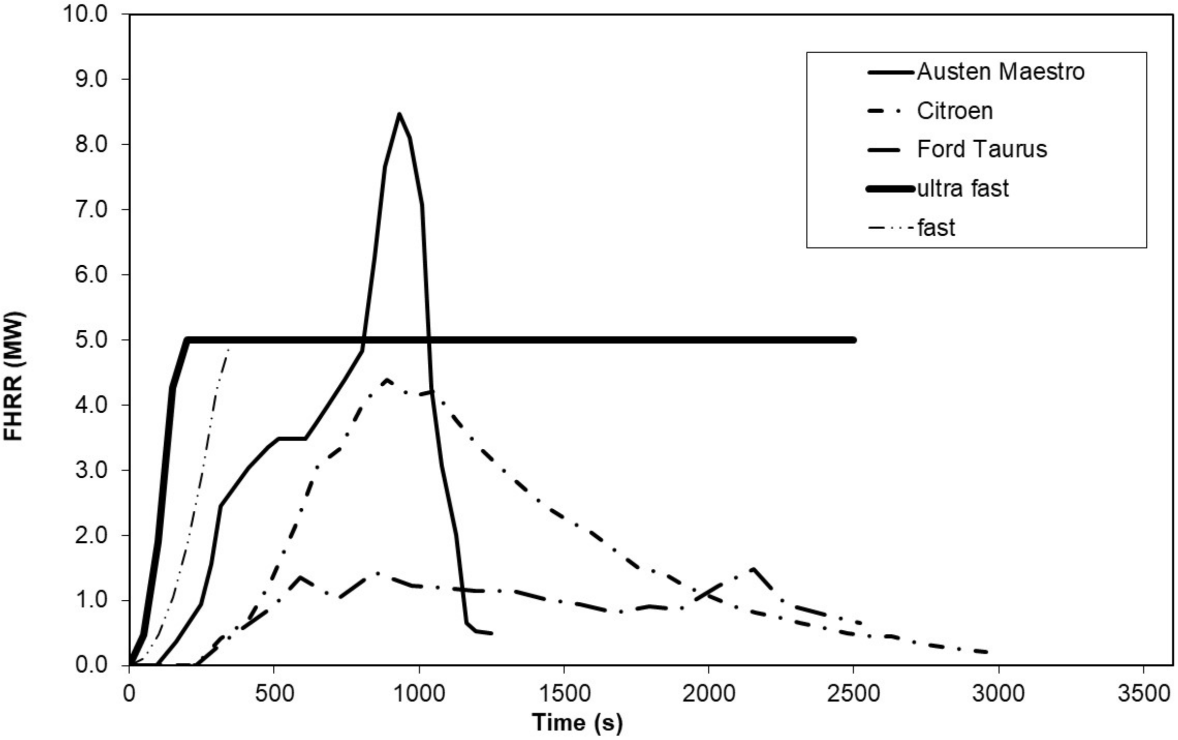


Figure 3-4: Graph. FHRR data for single passenger car fires [30].

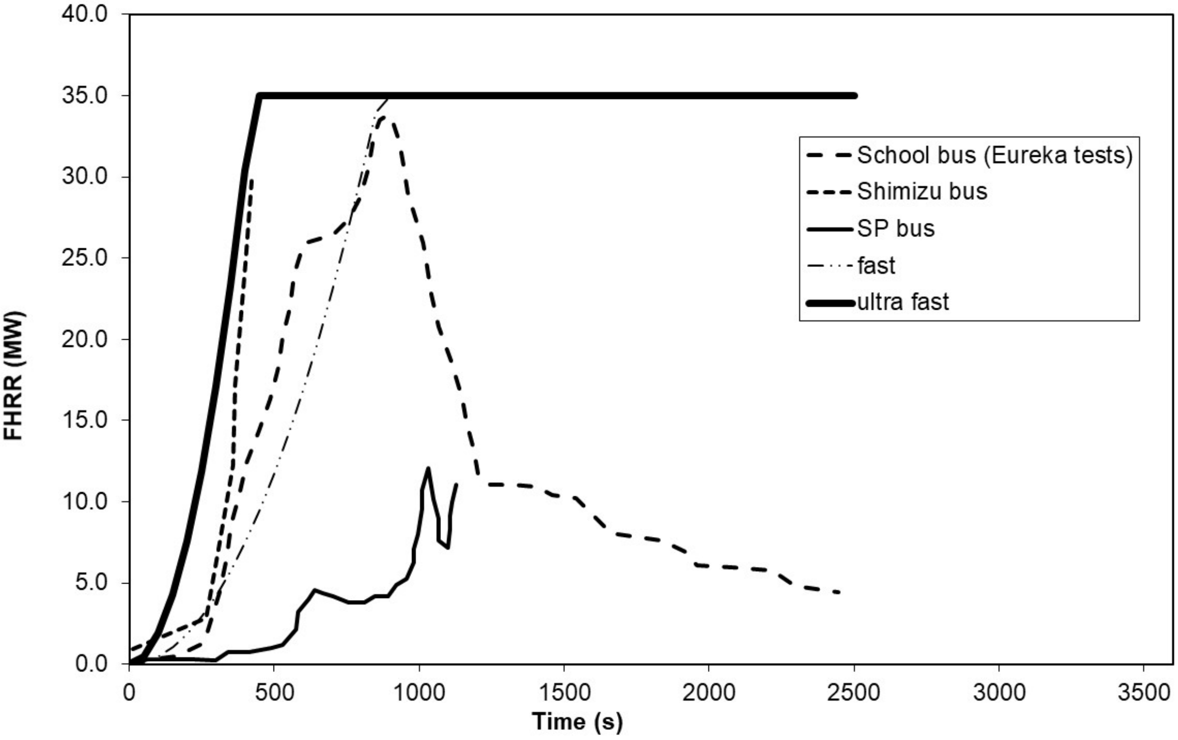


Figure 3-5: Graph. FHRR data for bus fires [26] [30].

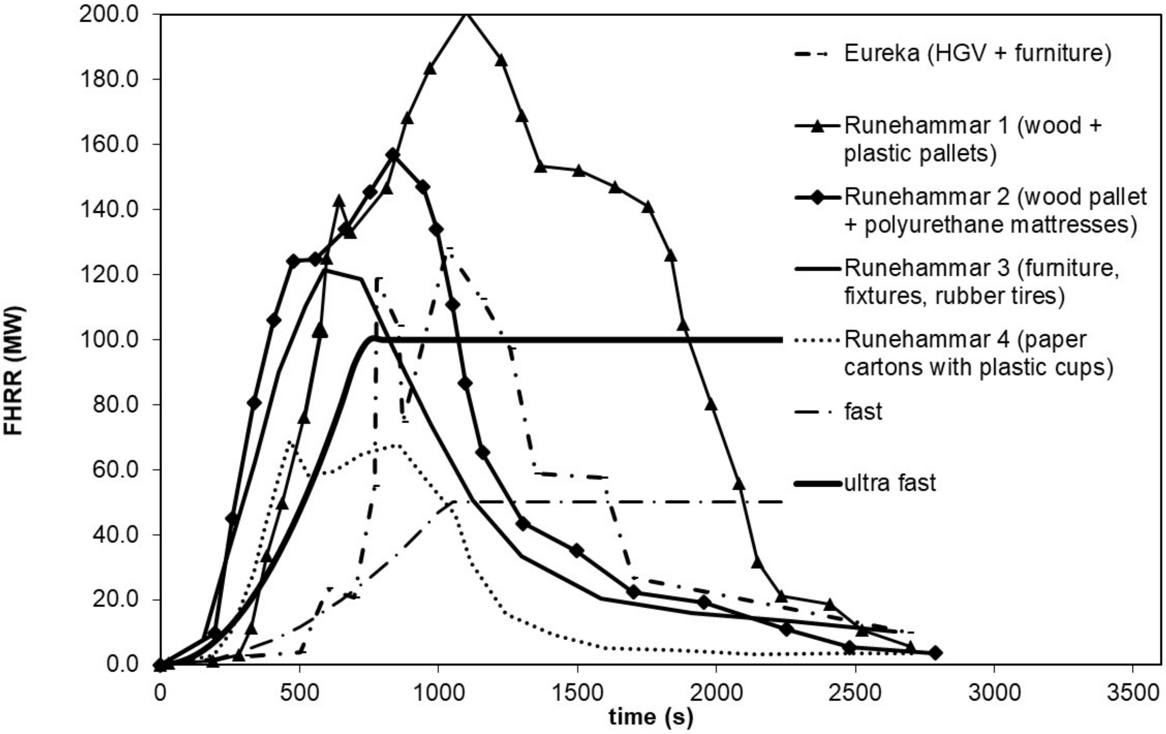


Figure 3-6: Graph. FHRR data for heavy goods vehicle fires [27] [41].

Fire soot yields and heat of combustion are also necessary for EVS design when considering tenability of the environment. For single vehicles fires there are two studies that report detailed yields of combustion products, including irritant gases [42] [43]. Table 3-2 provides some data. Soot yields are reported for other transport vehicles with data repeated in Table 3-3.

For HGV fires, similar data are not readily available and it is necessary to apply some assumptions as follows:

- The cab of the HGV will have a similar heat of combustion and combustion product yield to an automobile.
- For the HGV load a variety of commodities could be present, such as furniture, wood (pallets), plastics and so on.

Based on this, Table 3-4 provides the fire properties for some selected materials as derived from published handbook data [30].

Tanker fires are noted in NFPA 502 to have a potential FHRR of 300 MW. There are no data available for a tanker fire test [44] and the FHRR will depend on the circumstances around the event leading to a fire [10]. Tests are reported for pool fires, which can be used to represent a major fuel spill. Pool fire tests of gasoline in a laboratory have a FHRR of around 2.4 MW/m^2 [10].

Roadway geometry and pool size significantly affect the FHRR, and should be considered when analyzing tanker fires. The major concern with a tanker fire is the fuel spill, which can cover a large area, and then the ignition of that pool. Ingason and Li provide testing and analysis of fuel spills on a roadway [44]. It is noted that pool fire tests are usually conducted in pans with a depth of fuel on the order of 70 mm or more, producing an average FHRR per unit area of 2 MW/m^2; however, in contrast a pool of gasoline on a roadway is noted to have a depth an order of magnitude less than this. The decreased pool depth results in a lower FHRR per unit area, for instance, 1.5 MW/m^2 when the depth of the pool is 7 mm and 0.8 MW/m^2 when the depth is 2-3 mm [44]. Tests were conducted to understand the pool spread rate for different flow rates and the FHRR. The testing demonstrated an FHRR of around 0.8 to 1.0 MW/m^2 for a pool depth of around 2 mm. The FHRR was 30-40% of the value that would be predicted if the fuel spill were assumed to represent a standard pool fire. Additional testing by Klein et al. investigated the effects of tunnel grade and cross slope on the size of the pool fire [45]. The results showed that increasing the cross slope from 1% to 4% could reduce the FHRR by 75% due to reduced spill area (i.e. reduced spread rate due to fuel reaching drains sooner).

Table 3-2: Fire products, automobile tests SP (2006) [42] and INERIS (2018) [43].

Parameter	Units	Car 0 Gasoline (SP)	Car 1 Gasoline (INERIS)	Car 2 Gasoline (INERIS)	Car 3 Gasoline (INERIS)	Car 4 Electric vehicle (INERIS)
Mass before	kg	No data	936.0	1404.0	1564.0	1501.0
Mass burned	kg	109.0	192.0	275.0	262.0	278.5
Energy released	MJ	3815	6890	10600	10000	8540
Heat of combustion	MJ/kg	35.0	35.9	38.5	38.2	30.7
Yields (kg/kg fuel)	kg/kg fuel	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
HCl	kg/kg fuel	0.0130	0.0038	0.0029	0.0033	0.0030
HF	kg/kg fuel	No data	0.0012	0.0011	0.0007	0.0023
HCN	kg/kg fuel	0.0016	0.0003	0.0002	0.0005	0.0002
CO_2	kg/kg fuel	No data	0.9654	0.9695	0.9733	0.9698
CO	kg/kg fuel	0.0630	0.0229	0.0211	0.0194	0.0183
NO	kg/kg fuel	No data	0.0013	0.0010	0.0015	0.0012
NO_2	kg/kg fuel	No data	0.0006	0.0006	No data	0.0005
SO_2	kg/kg fuel	0.0050	No data	No data	0.0013	No data
C_3H_4O	kg/kg fuel	0.0003	No data	No data	No data	No data
CH_2O	kg/kg fuel	0.0011	No data	No data	No data	No data
Hydrocarbons	kg/kg fuel	No data	0.0045	0.0037	No data	0.0045

Table 3-3: Soot yields [27].

Vehicle	Soot yield (g/g fuel)
Private car (steel)	0.095
Private car (plastic)	0.080
Public bus	0.050
Heavy goods truck	0.02 to 0.025

Table 3-4: Carbon monoxide yields [10].

Material	Large-scale tests (g CO/g fuel)
Wood	0.058
Paper	0.058
Textiles	0.051
PVC	0.116
PUR	0.160
Polystyrene	0.220
Polyethylene	0.060

3.3.5 Standards and Guidelines

A range of FHRRs per NFPA 502 is provided in Section 3.3.4. These values are not mandated by the standard and are meant as a guide regarding industry practice. FHRRs used in other jurisdictions are summarized in a PIARC report Design Fire Characteristics for Road Tunnels [25]. Australia and Japan are noted to be locations where FFFS are routinely employed. A summary is provided in Table 3-5.

Table 3-5: Design fires for various countries [25].

Country	Design fire (MW)	Remarks
Australia	50	FFFS included
Austria	30	Impact of 50 MW considered if the tunnel is high risk
France	30 to 200	200 MW if dangerous goods are transported
Germany	30 to 100	Depends on length of tunnel and heavy goods vehicles
Greece	100	No data
Italy	30 to 50	100 to 200 MW if tankers allowed
Netherlands	5 to 200	Varies with vehicle type, risk assessment used
Norway	20 to 100	Depends on risk (length, vehicle count/type), longitudinal ventilation
Portugal	Varies	Depends on vehicle type, 100 MW considered in recent tunnels
Singapore	30 to 200	Depends on vehicle type
Spain	>30	Minimum fire size
Switzerland	30	For smoke extraction
UK	5 to 100	Varies with vehicle type
USA	30 to 300	Depends on vehicle type, 300 MW if dangerous goods allowed

3.3.6 New Energy Carriers

New energy carrier vehicles (alternative fuel vehicles) are vehicles powered by fuel sources including natural gas (compressed or liquefied), hydrogen, biodiesel, ethanol, and electric vehicles (batteries). The use of new fuel sources raises several concerns when a tunnel environment is concerned. The principal concerns include explosion risk for fuels such as compressed natural gas or hydrogen, fire fighting response strategies, thermal runaway in the case of battery fires, and the somewhat uncertain nature of a design fire for these alternative fuels [24] [46].

Regulations typically limit or prohibit the use of alternative fuel vehicles in U.S. tunnels. In cases where fuels are allowed, they are limited in type and quantity. The Port Authority of New York and New Jersey limit alternative fuels in their facilities to vehicles using compressed natural gas or liquefied natural gas [47]. These vehicles are only permitted to use tunnels if the vehicle has a dedicated fuel system meeting specified regulatory requirements, if the fuel capacity of the vehicle does not exceed 150 pounds, and appropriate markings and symbols must be displayed. Similar restrictions are applied via the Code of Maryland for vehicles in tunnels such as the Baltimore Harbor and Fort McHenry Tunnels in Maryland [48].

For vehicles carrying compressed gases, one of the major safety features is the fuel tank and the pressure relief device [46]. The role of the relief device is seen in fire tests and incidents:

- In 2010 a study by the UK group BRE (Building Research Establishment) looked at full-scale burns of gasoline vehicles, with one case also involving a test of an LPG vehicle [49]. The LPG vehicle test had the vehicle positioned between two gasoline fueled vehicles, one of which served as the ignition source. The FHRR was not measured in this test, but the test did show that the LPG tank did not explode and that the pressure relief device functioned as designed to vent the LPG fuel in a controlled manner.
- A CNG bus fire incident in The Netherlands in 2012 [50] involved a fire starting in the engine compartment of the bus, which ultimately spread to rest of the bus and caused the cylinder pressure relief device to activate. The flames from the cylinders extended 15 to 20 meters for about four minutes. The flames did not cause any injuries, however, there were questions raised regarding what impact these flames would have had in a tunnel fire.
- Fire fighting strategies for natural gas vehicles generally include approaching the vehicle with caution (e.g. approaching from the front of the vehicle if the cylinder is at the rear), and allowing the pressure relief device to fully relieve the cylinder pressures if possible by limiting water application to the cylinder where it is safe to do so [51].
- For hydrogen fuel vehicles, the response is like natural gas fires although it is noted that the flame is invisible. In some cases, if safe to do so, guidelines advocate allowing the fire to burn [52].

With the development and implementation of electric vehicles research has been conducted to understand how these fires burn and how first responders can suppress them. Full-scale fire tests with an electric vehicle show a similar FHRR to a gasoline fueled vehicle and similar order of magnitude for combustion product yields [53]. Some key fire parameters for vehicles is summarized in Table 3-6.

Table 3-6: Key fire parameters for electric and gasoline vehicles [53].

Manufacturer and vehicle	**Manufacturer 1, electric (EV1)**	**Manufacturer 1, gasoline (ICE1)**	**Manufacturer 2, electric (EV2)**	**Manufacturer 2, gasoline (ICE2)**
Fire heat release rate (MW)	4.2	4.8	4.7	6.1
Heat of combustion (MJ/kg)	29.8	35.9	30.7	36.4
CO yield (g/g fuel)	0.049	0.063	0.042	0.057
CO_2 yield (g/g fuel)	2.172	2.646	2.2208	2.6278
THC yield (g/g fuel)	0.0115	0.0124	0.0103	0.0099
NO yield (g/g fuel)	0.0024	0.0035	0.0028	0.0027
NO_2 yield (g/g fuel)	0.0009	0.0016	0.0013	0.0015
HF yield (g/g fuel)	0.0073	0.0032	0.0053	0.003
HCl yield (g/g fuel)	0.0100	0.0104	0.0069	0.0078
HCN yield (g/g fuel)	0.0005	0.0009	0.0005	0.0006

Figure 3-7 provides FHRR profiles for alternative fuel vehicles [54]. There are several curves on this figure, and although results vary from one test to another, there is some consistency in the FHRR results shown on this chart. The peak FHRR is around 5 MW and the time to reach this peak is approximately 20 minutes. This is significant because the profile shows similar results for regular gasoline vehicles and electric vehicles.

In terms of fire fighting for electric vehicles:

- Water is the recommended suppressant for electric vehicle fires [55]. Per NFPA, large amounts of water should be used to fight high voltage battery fires and to cool the battery [55]. The NFPA has also determined the volume of water necessary to extinguish fires trends with the size of the battery [56]. It was also found that firefighter access to the battery has a significant, but not yet quantified, effect on the time needed to suppress the fire [56].
- A concern for using water to extinguish an electrical fire is the risk of electrocution. Prior to the NFPA study referenced above, it had previously been concluded that using water on electric vehicle fires does not create a risk of electrocution. In the NFPA study regarding fire suppression for electric vehicles, this conclusion was reaffirmed [56].

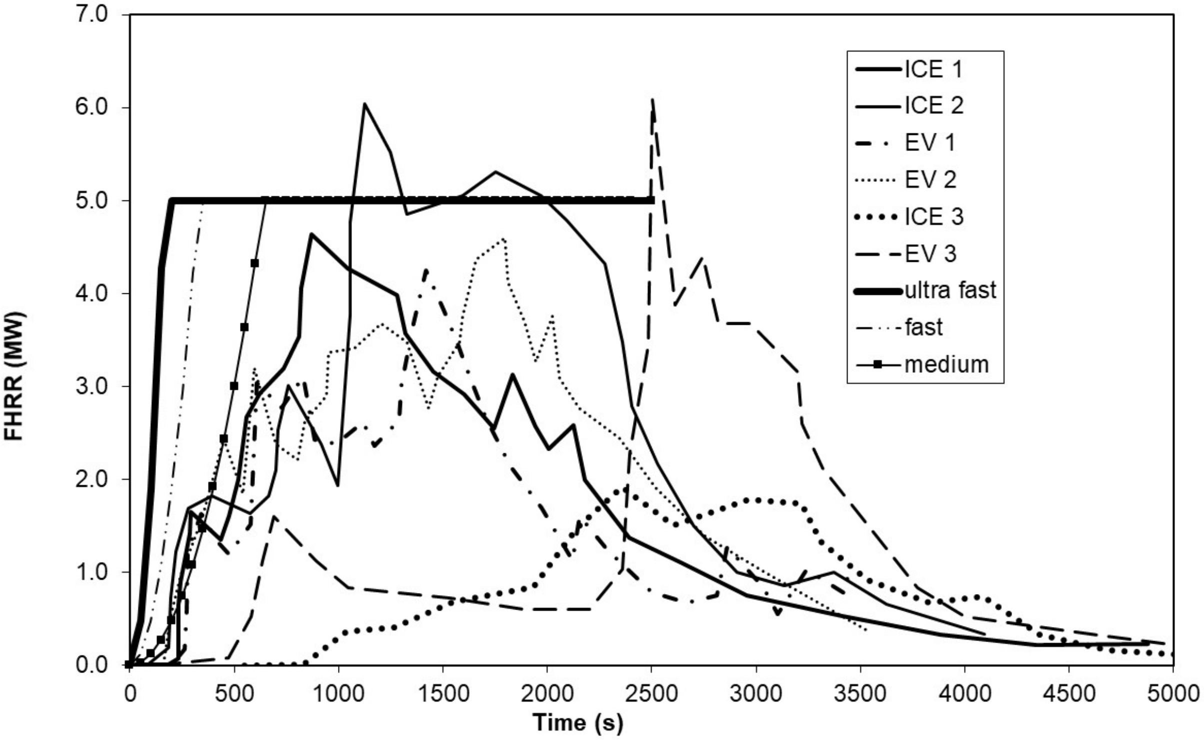


Figure 3-7: Graph. FHRR profiles for gasoline and electric vehicles [53] and [54].

New energy carriers represent an evolving area of research for the industry, and this is especially true when considering the topic of FLS and FFFS in tunnels. The review herein demonstrates that the risks might not be greater, simply different. For first responders, identification of the vehicle and the fuel type is critical. For many vehicles identification is achieved via a label or through the knowledge of fire responders to correctly identify the vehicle. The identification process is critical for responders to determine the best way to approach an incident and initiatives are being developed to standardize identification [57].

3.4 Fixed Fire Fighting Systems

3.4.1 General Overview

The primary effects of an FFFS are decreasing both the fire growth rate and peak FHRR. These reduce structure damage, irritant production, backlayering of smoke, and temperatures within the tunnel [24]. FFFS will also cool the surrounding area and reduce the risk of fire spread for HGV fires. NFPA 502 provides information on the FHRR for tunnels with an FFFS (see Section 3.3.4). It is important to note that tests show the FFFS must be activated early to have this effect. If activated too late, the fire could overwhelm the suppression system and the FHRR reduction will not occur [24].

As the fire size increases, fire fighter's effectiveness decreases. A typical level of heat exposure for a fire fighter is 3 kW/m^2 for 10 minutes (hazardous condition) or 4-4.5 kW/m^2 (extreme) for 1 minute [58]. Results from the Runehamar tests showed that the extreme radiation heat flux level was reached after 5-10 minutes [59] from ignition of the fire. In those cases, FFFS are the only option of delivering water to the fire and possibly achieving fire suppression. Additionally, by use of FFFS, damage to tunnel structure is limited, which has both operational and financial benefits. The tunnel can reopen sooner, with fewer costly repairs.

The inclusion of an FFFS in road tunnels is typically required in Australia and for some classes of tunnels in Japan [60] [24]. Other countries, including the United States, suggest that FFFS be considered when evaluating the FLS design of a tunnel.

3.4.2 Types of FFFS and Impact on Fire

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 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 means mist systems use less water. Table 3-7 provides a summary of the system features, along with advantages and disadvantages.

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 3.4.3.

- **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 and plastic 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) [4].
- **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, even though the estimated potential peak FHRR was 136.5 MBtu/hr (40 MW). Temperatures downstream of the fire were reduced from a range of 392°F to 570°F (200°C to 300°C) to less than 212°F (100°C) [61].

Scale tests by Li et al. sought to investigate the reduction in FHRR achieved using various FFFS setups and provide information on the design fire reduction expected. The tests used a model tunnel 49.2 ft. (15 m) long, 9.2 ft. (2.8 m) wide, and 4.6 ft (1.4 m) high (represents a 1:4 scale). FFFS provided coverage of 12.5 m of the tunnel. An axial fan directed smoke down the tunnel towards an exhaust hood. The main fire vehicle and downstream target were simulated using stacked wooden pallets. The peak FHRR of the main vehicle was calculated to be 3 MW, which equates to 100 MW in full-scale (a large HGV) [1].

These tests showed that prompt activation of the FFFS is important for achieving the best reduction in FHRR. Early activation pre-wets unburnt fuel, which then limits further spread of the fire. For a late activation of the FFFS, cooling of burning surfaces is more difficult to achieve. The tests showed that a water flow rate of 0.12 gpm/ft^2 (5 mm/min) (0.25 gpm/ft^2, 10 mm/min in full-scale) to 0.18 gpm/ft^2 (7.5 mm/min) (0.37 gpm/ft^2, 15 mm/min in full-scale) was able to fully suppress an unshielded fire. A lower applicate rate of 0.06 gpm/ft^2 (2.5 mm/min) (0.12 gpm/ft^2, 5 mm/min full-scale) was only able to reduce the peak FHRR to 50% of the free-burn case [1].

The effects of water application rate were also investigated on shielded fire loads, where a steel plate was added on top of the main fire load. This configuration reduces the ability of FFFS spray to reach the fuel. In the shielded case, the authors concluded that increasing the water application rate from 0.12 gpm/ft^2 to 0.18 gpm/ft^2 (5 mm/min to 7.5 mm/min) only reduced the peak FHRR 9% when compared to the free-burn test. The results of these two tests are shown in Figure 3-8. The 0.12 gpm/ft^2 (5 mm/min) test case reduced the peak FHRR from 3 MW to 1 MW.

Table 3-7: Deluge and water mist system characteristics.

Characteristic	Deluge	Water mist
General	Open nozzles, attached to piping, arranged in zones, connected to valves activated to deliver water to desired location. Typical zone dimensions are 30 ft (9 m) wide and up to 100 ft. (30 m) long (i.e. for two lanes of traffic). Water mains wet to valves.	As per deluge
Drop size ($DV_{0.9}$ – 90% of droplets this size or smaller)	0.04 inches (1,000 µm)	Class C: > 0.02 in. (400 µm) Class B: 0.008 to 0.02 in. (200 to 400 µm) Class A: < 0.008 in. (<200 µm or less) [62]
Pressure	21.8 psi to 72.5 psi (1.5 bar to 5 bar)	Low: < 232 psi (16 bar) Medium: 232 to 870 psi (16 to 60 bar) High: > 870 psi (60 bar) [62]
Pipe materials	Galvanized steel, or similar depending on project requirements	Stainless steel may be required
Proprietary specific	Deluge systems tend not to be specific to one supplier and 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 fire suppression 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. The droplets are smaller and entrainment into the fire plume occurs.
Water application rate examples	**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)	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) [11]
Pros	Relatively simple to design using standard sprinkler system components, potentially fewer components than a 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; water filtration may be needed to eliminate small particles. Less direct cooling of the fire's burning surface and small droplets might be more susceptible to drift.

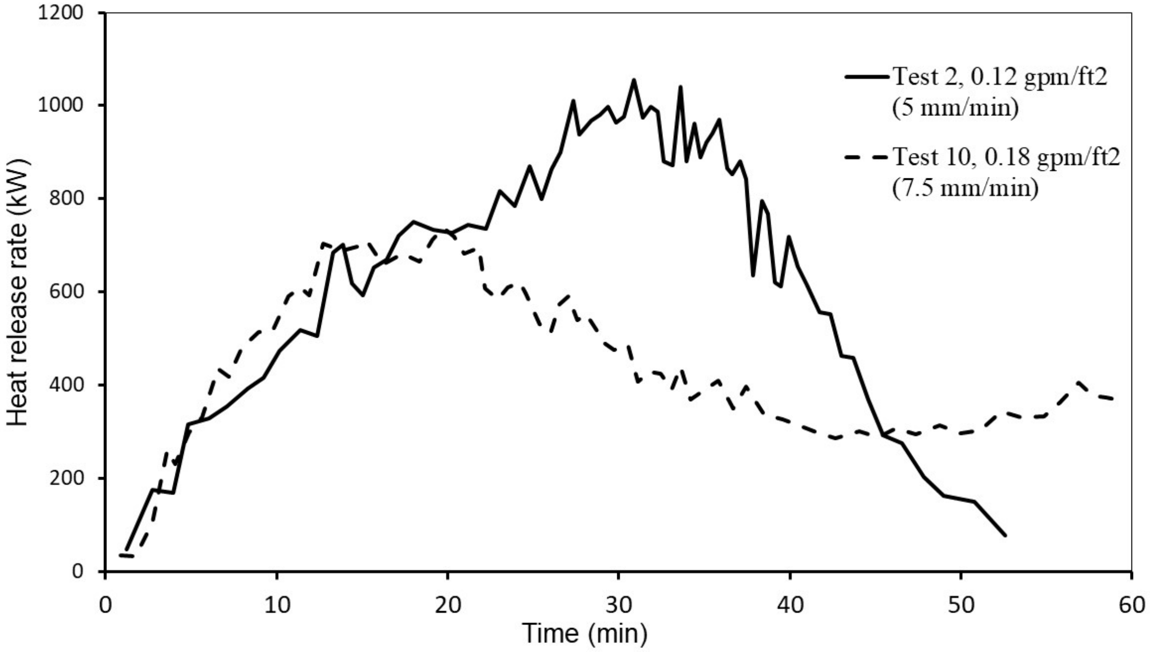


Figure 3-8: Graph. Effects of water application rate on shielded fire load [1].

The model scale setup also allowed for testing other factors, including: nozzle types, tunnel cross section geometries, FFFS zone length, and longitudinal air velocity. The authors concluded that across all the scenarios, the use of an FFFS reduces the FHRR by at least 50%, with a reduction of 70% likely. The tests that reduced the FHRR by less than 70% used a water application rate of 0.06 gpm/ft^2 (2.5 mm/min) (0.12 gpm/ft^2, 5 mm/min full-scale) or did not have shielding on the front and back of the fuel source (exposing the fuel to high longitudinal velocities).

Tests by Chen et al. used a 1:5.5 scale tunnel (47.2 ft. long, 5.9 ft. wide, 3.9 ft. high or 14.4 m long, 1.8 m wide, 1.2 m high) to look at the cooling effects of FFFS. The test setup used a heptane pan as the fuel source, with one sidewall nozzle mounted above the pan. The tests varied the upstream air velocity and compared the temperature profiles and backlayering distance with and without water spray. The scale water application rate was 0.06 gpm/ft^2 (2.3 mm/min) (0.13 gpm/ft^2, 5.4 mm/min in full-scale). The upstream air velocities varied from zero to 307 fpm (1.56 m/s) (335 to 708 fpm, 1.7 to 3.6 m/s full-scale). The heptane fuel load was calculated to produce a peak FHRR of 258 kW (18 MW full-scale) [63].

The test results showed that at scale velocities between 0.72 and 1.56 m/s, mid-height gas temperatures downstream of the fire source ranged from 302 to 662°F (150 to 350°C). When the nozzle was activated, the temperatures were reduced to 25 to 90°C, showing the water spray had a significant cooling effect [63].

Sun et al. used model tests to investigate the ability of a mist system to act as a water curtain to bound a fire zone. For naturally ventilated (no upstream air velocity) tests, the mist contained smoke and high temperatures to the fire zone. In cases with longitudinal ventilation, the mist did not contain smoke, but did reduce temperatures [64].

Ingason et al. used laboratory testing to investigate the effect of FFFS on a liquid fuel spill. These tests showed that the use of FFFS provided cooling of the fire plume but did not affect (either increase or decrease) the FHRR. The testing also showed that the addition of aqueous film forming foam (AFFF) to the FFFS did reduce the FHRR by 50% but the system was not able to extinguish the liquid fuel spill [5].

3.4.3 Full-Scale Testing

A comprehensive summary of fire tests is provided in the most recent PIARC report and recently published textbooks [10] (Table 16.1) [11] (Appendix 4). Further detail on a selection of the tests is given in the following subsections.

3.4.3.1 SOLIT Tests

Two series of tests were conducted as part of the SOLIT (Safety of Life in Tunnels) Project. The result of the first test series were published in 2007, and the second test series (SOLIT^2) in 2012. The review herein focuses on the SOLIT^2 project which involved testing using a water mist system [65]. Fire tests were carried out in the San Pedro de Anes Tunnel in Spain. The fire loads were a mock-up of a truck fire load, consisting of standard wood pallets, and a diesel pool fire. The wood pallet fire load had a potential FHRR of 150 MW (408 pallets, 9600 kg, 140 GJ) and the ignition source was three gasoline pools distributed throughout the fire load. Ventilation was longitudinal and a target was placed 5 m downstream of the fire. A PVC tarpaulin was used to cover the fire load.

The work was focused on compensatory effects of an FFFS for design aspects including ventilation, distance between exits, passive fire protection and fire fighting [66]. Key measurements included FHRR, temperature, visualization of smoke movement and fire spread. The major outcomes of the tests included a demonstration of the following positive effects of the FFFS [66]:

- Temperature reduction – small reduction in temperature immediately above the fire, reduced area of high temperatures (around 200 degrees C, [66] Figure 4 through 7).
- Temperature reduction – temperatures downstream of the fire reduced to around 60 degrees C, from over 100 degrees C without an FFFS ([66] Figure 8 and 9).
- Radiant heat flux – reduced from more than 10 kW/m^2 to less than 1.5 kW/m^2 with the FFFS operating ([66] Figure 13 and 14).
- Fire spread – fire spread, indicated by increased temperature, was effectively prevented for up to 30 minutes downstream of the fire ([66] Figure 15).
- FHRR – potential FHRR of 150 MW kept to around 40 to 50 MW with the FFFS operating ([66] Figure 17 and 18).
- Self-rescue – reduced temperatures (to within tenable limits) ([66] Figure 23 and 24) and reduced carbon dioxide concentrations (more than 10% CO_2 to less than 2% with the FFFS) ([66] Figure 25 and 26).
- Protection of structure – significant reduction in the internal temperature of a concrete sample during the tests ([66] Figure 31).
- Ventilation – the FHRR was around 30 MW and a ventilation velocity of 2 to 2.5 m/s was sufficient to control smoke with no backlayering [65].

Discussion on compensatory approaches is provided in the report in relation to the following impacts of the FFFS [66]:

- Self-rescue – reduction of the critical velocity (longitudinal vent) and improved smoke capture (transverse), potential to increase distance between exits.
- Fire fighting – reduced risk of fire spread, reduced heat fluxes, reduced FHRR.
- Structural fire protection – reduced time-temperature curve for the structure, potential to avoid passive protection layers, reduced repair time/cost following a fire.

Water application rates were not published in the reports.

3.4.3.2 Runehamar Tunnel

The Runehamar tunnel is an out of service, two lane road tunnel located in Norway (approximately 28 ft. (8.6 m) wide by 16.5 ft. (5.0 m) high). The Research Institutes of Sweden (RISE) have conducted multiple full-scale fire tests in the tunnel, involving heavy goods vehicle mockups and deluge systems. One set of six tests was performed in 2013, and another set of six in 2016 [2] [3].

In both sets of tests, the fire source was the same: 420 standard Euro (EUR) wooden pallets elevated on concrete slabs, with sheet steel shielding the ends and the top of the pallet stack. The steel plates were used to make it difficult for water to penetrate directly to the fire load during the test; the configuration was not noted to have any basis in standardized HGV loading [3]. The energy load of the fire source was estimated to be 180 GJ, with a predicted peak FHRR of 100 MW [2].

The suppression system setup was also the same between the two sets of testing. The main pipe was located near the tunnel side wall, with nozzles directed towards the fire source. The total zone length was 98 ft. (30 m), and contained six nozzles, evenly spaced. The tunnel width was 8.6 m. The twelve tests varied FFFS application rates, nozzle types, and type of shielding. A longitudinal velocity of 590 fpm (3 m/s) was generated by fans upstream to prevent backlayering. During the 2016 tests, the deluge system was activated 4 minutes after ceiling temperatures reached 286°F (141°C) [2]. The tests also included a target stack of 21 wooden pallets placed 16.5 ft. (5 m) downstream of the fire source, within the deluge zone. The location and size of the target were the same between the 2013 and 2016 tests.

Test 6 of the 2013 tests was an unsuppressed, free burn test (the test was close to an unsuppressed, free burn test as the FFFS was activated very late and the pipe accidently broke at around activation, and thus FFFS had only a very minor influence on the fire development). The peak FHRR was between 70 and 80 MW. Small (model) scale tests suggested a likely higher peak FHRR (more than 100 MW) [1], however, the wood in the full-scale tests contained between 15% to 20% moisture content, resulting in a reduced FHRR relative to the dry wood used in the model scale. The 2003 Runehamar tests [41] had a much larger peak FHRR, but these tests used a different fire load configuration and a restricted tunnel cross section at the fire site.

The remainder of the 2013 tests used a water application rate of 0.25 gpm/ft^2 (10 mm/min), with a total flow rate of 595 gpm (2250 L/min) [3]. Nozzle types and flow rates were varied in the 2016 tests [2]. Figure 3-9 shows only the effects of varying the water application rate and nozzle type (all other variables held constant). The water application rates in this selection of tests vary between 0.15 and 0.25 gpm/ft^2 (6 and 10 mm/min), with the resulting peak HRR ranging from 13 to 28 MW (a reduction of 64% to 83%). The only test where the target stack of pallets (downstream) ignited was the free burn test in 2013. All tests where water was applied prevented the fire from spreading to the target [2].

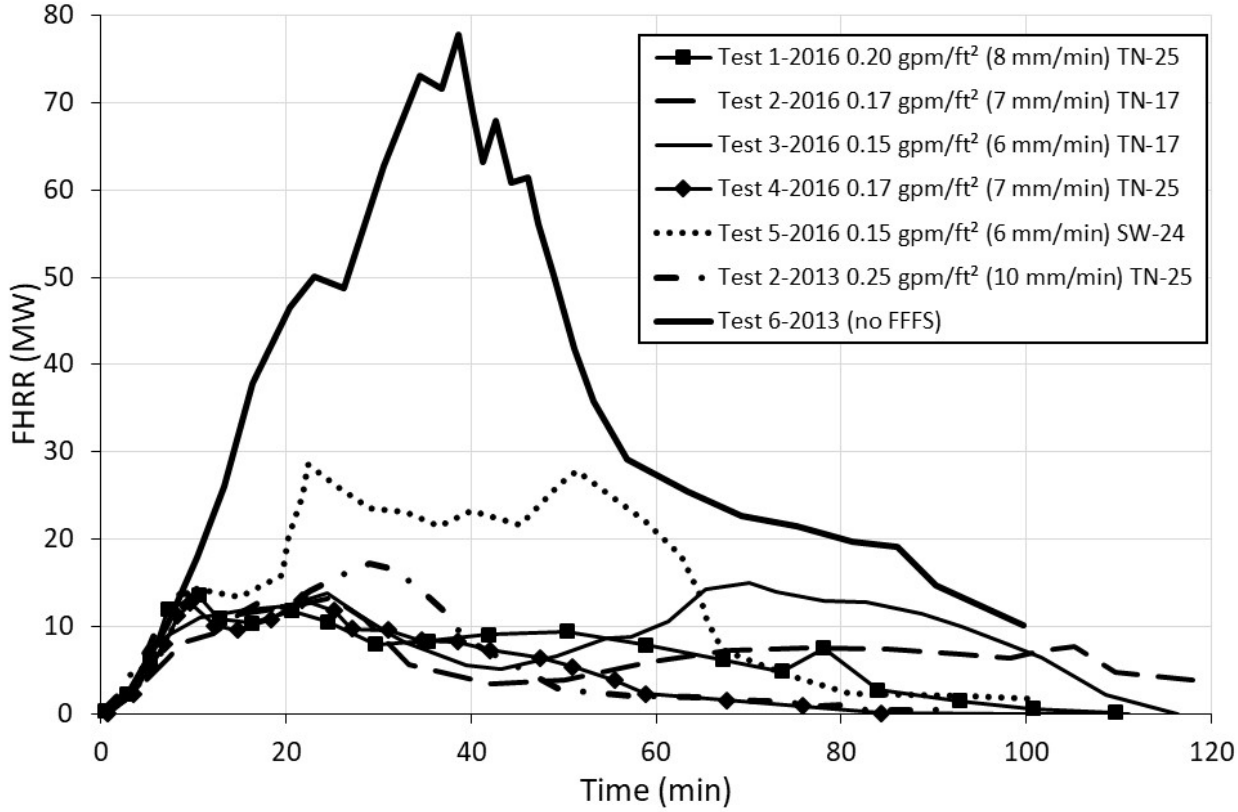


Figure 3-9: Graph. FHRR curves for a selection of Runehamar tests [2], [3].

3.4.3.3 LTA Tests

A series of tests was performed in Spain for the Singapore Land Transport Authority (LTA) to investigate the fire heat release rate of heavy goods vehicles in tunnels. The fire source in these tests was like the Runehamar tests, and contained 180 wooden pallets and 48 plastic pallets, shielded on three sides by steel plates. A plastic tarp covered the other two exposed sides. The tunnel at the fire site was 17 ft. high and 24 ft. wide (5.2 m by 7.3 m). A longitudinal velocity of 600 fpm (3 m/s) was generated upstream to prevent backlayering. Similar to the Runehamar tests, a target stack of 38 wood and plastic pallets was placed 16 ft. (5 m) downstream of the source to assess fire spread [4].

The test used a suppression system consisting of 46 nozzles distributed over a length of 165 ft. (50 m). Water application rates of 0.20 to 0.30 gpm/ft^2 (8 and 12 mm/min) were tested; the deluge system was activated 4 minutes into the test [4].

Test 7 of the LTA tests was a free burn test, which reached a peak heat release rate of 150 MW (shown in Figure 3-10). Test 2 used directional nozzles and a water application rate of 0.20 gpm/ft^2 (8 mm/min), which limited the peak FHRR to 40 MW. Test 4 used standard spray nozzles and an application rate of 0.30 gpm/ft^2 (12 mm/min), limiting the peak HRR to 30 MW [4].

The target stack of pallets (downstream) was ignited in the free-burn test (test 7). Test 4 with water application, limited the heat flux at the target to 1.3 kW/m², which is significantly less than the minimum ignition heat flux of 10 kW/m². Heat flux results for Test 2 were not provided [4].

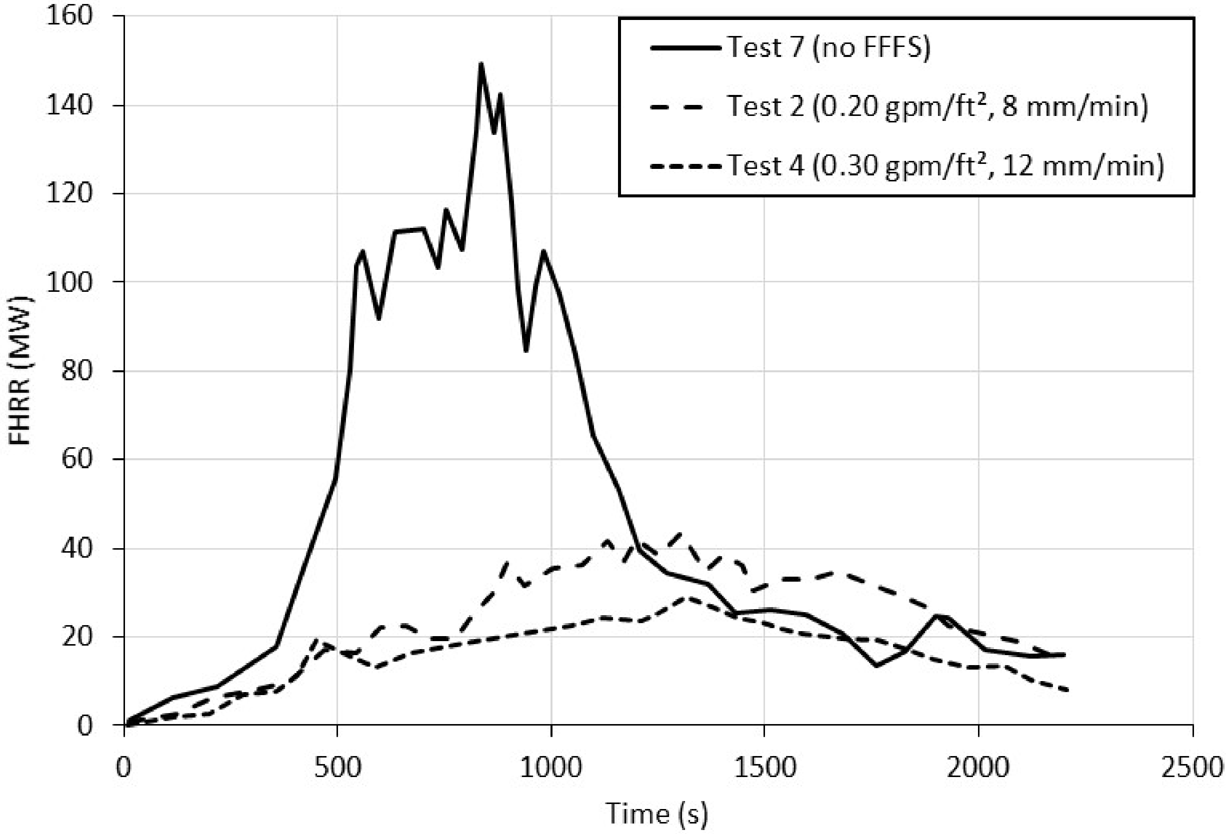


Figure 3-10: Graph. FHRR curves for a selection of LTA tests [4].

The LTA tests show that a fire with a peak FHRR of 150 MW is suppressed to 40 MW with the application of 0.20 gpm/ft^2 (8 mm/min) of water. For reference, the LTA fire can be compared to an example design fire of 120 MW, with an ultrafast growth rate as defined in NFPA 92. NFPA 92 Table B.7.1 states the time needed for an ultra-fast fire to reach 1.06 MW is 75 s [67] at a growth rate constant of 188 W/s^2. The t-squared design fire equation is then plotted in Figure 3-11 using this same growth rate, along with the LTA test HRR curve. This shows the LTA test well matches the ultra-fast, heavy goods vehicle design fire curve, though with a larger peak HRR. No fire inception period is assumed in this design fire curve, meaning the fire begins to grow per the t-squared curve immediately after ignition. In the test the fire ignition source was located within the wood pallet load; in a real fire, the growth rate would be slower in the initial phases until the fire spread to the load.

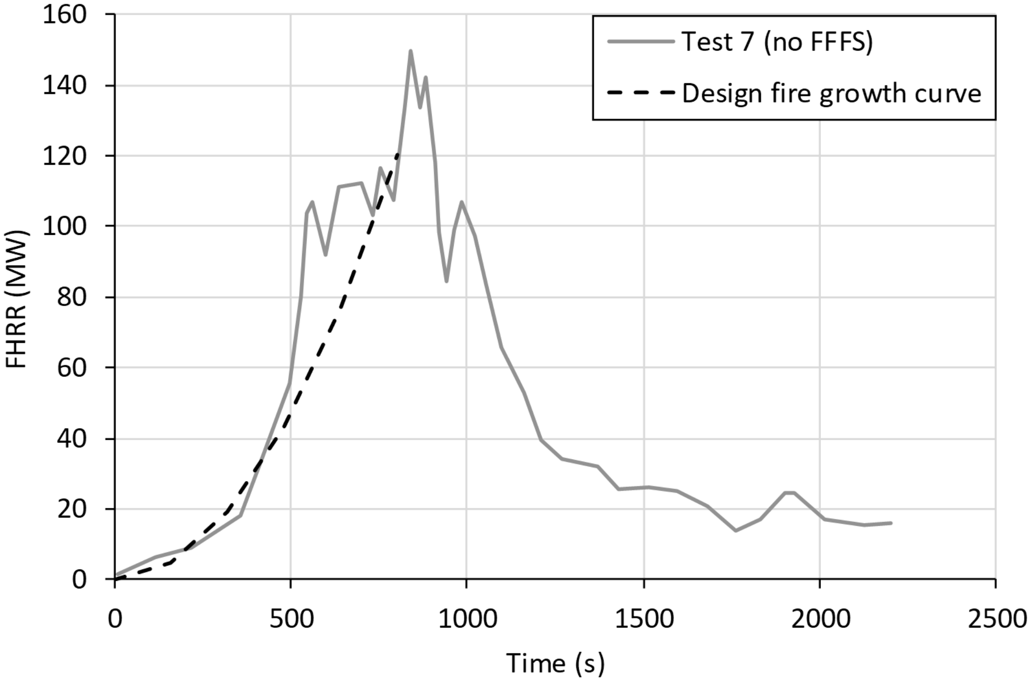


Figure 3-11: Graph. LTA test versus design fire HRR curves.

3.4.3.4 Additional Full-scale Tests

Tests of a proprietary low pressure water mist system were conducted in the test tunnel at San Pedro De Anes in 2018 [68]. Tests were of wooden and plastic pallets with a metal cover at the ends and on top. Details of the system nozzles were as follows:

- Zone length 80 ft. (25 m)
- Longitudinal pipeline along the tunnel centerline (3MS) tests and two pipelines (5MS tests)
- Nozzles arranged in pairs or triples at each longitudinal location
- Nozzle K factors of 3.2 and 2.0

Fire tests included a free burn where the maximum FHRR was 243 MW. For a water application rate of 0.05 gpm/ft^2 (2.2 mm/min) and an upstream velocity of 850 fpm (4.3 m/s), the system (3MS) could keep the FHRR to 59 MW. For a water application rate of 0.13 gpm/ft^2 (5.2 mm/min) and an upstream velocity of 960 fpm (4.9 m/s), the system (5MW) kept the FHRR to 46 MW. In all tests with the FFFS spread of fire to a downstream target was prevented.

Fire tests of suppression systems have been conducted for applications besides tunnels, including parking garages and ship decks. These tests provide some useful insight into the ability of an FFFS to manage a vehicle fire.

Fire control and suppression was investigated for a parking garage configuration (three cars side-by-side), specifically looking at sprinkler and water mist systems [69]. The sprinkler system had a water application rate of 0.16 gpm/ft^2 (6.5 mm/min) at a pressure of 1 bar, and the mist system had a water application rate of 0.04 to 0.05 gpm/ft^2 (1.5 to 2.0 mm/min) at a pressure of 90 bar. Both systems had a nozzle operation temperature of 155°F (68°C). The fire originated under the vehicle. The performance of the systems was similar in terms of fire control (no spread to the neighboring vehicle), and slightly better for the water mist system for fire suppression (interior not involved). Both systems were concluded to provide adequate structural protection. One of the water mist tests used a surfactant additive but the results were not conclusive on the impact it had. FHRR was not measured in these tests.

Arvidson [6] looked at fire protection of cargo in a configuration typical to that seen on ship cargo decks. The investigation considered a standard deluge system with water application rates of 0.12, 0.25, and 0.37 gpm/ft^2 (5, 10, and 15 mm/min) with shielded and unshielded configurations. A water mist system (pressure of 84 bar) was tested with a water application rate of 0.14 gpm/ft^2 (5.8 mm/min). The fire load was a set of carboard boxes with plastic cups inside. The potential peak FHRR was 25 MW for six rows of boxes or 10 MW for two rows. The FFFS was activated when the convective FHRR was 3 MW. The test results showed the following:

- For an unshielded fire, water application rates of 0.25 gpm/ft^2 (10 mm/min) or greater could provide fast fire suppression, with the FHRR dropping from a peak of 5 MW to less than 1 MW in a matter of 2 to 3 minutes. For the lower water application rate of 0.12 gpm/ft^2 (5 mm/min), the system achieved fire control and took more than 20 minutes to achieve the same FHRR reduction. The water mist system performed notably poorer in these cases with a peak FHRR of 15 MW compared with 10 MW using a deluge system. The difference in performance can be attributed to the water mist droplets being unable to penetrate the fire plume and reach the seat of the fire.
- For shielded fires the water spray was not able to reach the fire and thus the performance of both systems was similar. There was also less dependence in these tests on the water application rate, although it was noted that tests at 0.37 gpm/ft^2 (15 mm/min) performed poorer than expected, which was likely due to the increased droplet size. The difference in the FHRR between water application rates of 0.12 and 0.25 gpm/ft^2 (5 and 10 mm/min) for these tests was minimal.

3.4.4 Impact of FFFS on Liquid Fuel Fires

To better understand the role of an FFFS on a liquid fuel spill fire it is helpful to review the different mechanisms involved in water droplet interaction with fire. The effectiveness of a water droplet in fire fighting is determined by the following factors [70]:

- Air velocity – droplets can be blown away from the fire
- Direct cooling – droplets that penetrate the fire plume and reach the burning surface to inhibit pyrolysis with the resultant steam diluting oxygen near to the fire
- Surface cooling – droplets that impact on walls, floor and ceiling of a compartment to provide cooling of those surface
- Vaporization – droplets that evaporate and thus become steam, contributing to cooling of the environment
- Pre-wetting – adjacent combustibles are pre-wet to prevent fire spread

The dominant extinguishing methods for action of water mist on a fire include [70]:

- Heat extraction through cooling of the fire plume, wetting/cooling of the fuel surface
- Displacement of oxygen and dilution of fuel vapor

For heat extraction, the mechanism of extinguishment will depend on the droplet diameter and the fuel. A smaller droplet diameter will result in less fuel surface cooling and more heat extraction through cooling. For fuels that do not produce combustible mixtures of fuel vapors at the surface (e.g., a typical solid fuel/ class A fire, such as wood) water mist is typically less effective because it cannot penetrate through the plume and char layer to the pyrolysis zone [70]. Water mist systems have been noted to be effective on class B (flammable liquid) fires [71]. For comparison, droplet diameters of 4 mm to 5 mm are quoted as optimal for plume penetration, while smaller droplet diameters, around 0.15 mm to 0.30 mm are optimal for a low flash point immiscible fuel [70]. Additives to water mist can help in some cases, depending on the type of liquid fuel and additive [71].

3.5 Computer Models

3.5.1 Combustion Modelling Methods

Combustion is arguably the most challenging aspect of conducting a CFD model of an FFFS in a tunnel. Modeling fire and predicting its suppression with CFD is hampered by the difficulty in accurately representing all the physical phenomena over a range of length and time scales and phases, such as turbulence, radiation heat transfer, combustion, material properties, numerical accuracy, suppression, and pyrolysis.

This is not to say that the challenge is insurmountable. CFD modeling of combustion and fire suppression is a rapidly maturing field. This section provides a brief overview of the combustion modeling techniques typically applied in tunnel FLS CFD analysis as they relate to inclusion of an FFFS. Combustion is primarily modeled in one of two ways in a CFD framework; volumetric heat source or mixing controlled. A brief overview of the two approaches is provided in Table 3-8.

For the purposes of this work, methods to model combustion with active FFFS are categorized as follows:

1. Volumetric heat source.
2. Mixing controlled without solid pyrolysis.
3. As per 2) with fire spread via ignition temperature of a target.
4. As per 3 with fire suppression via empirical equations.
5. Mixing controlled with solid fuel pyrolysis.

The mixing controlled approach to combustion modeling can take a variety of forms. This is explained further in the subsections below, which summarize some methods available and how they can be used to model combustion and the effects of FFFS. Other techniques may be available and this area of knowledge and practice is evolving.

Table 3-8: Comparison of combustion modelling methods.

Parameter	**Volumetric heat source**	**Mixing controlled combustion models**
Description	With this method, the combustion process is not modeled directly. Instead an amount of heat and smoke is injected corresponding to the desired fire size and design smoke flow rate. Radiation is not typically modeled and can be subject to inaccuracy because fire temperatures are not accurately predicted.	With this method, a quantity of fuel (Z=1) is injected into the domain. Combustion occurs when the fuel encounters air (Z=0) and sufficient heat. The fuel and combustion chemistry is used to determine the quantity of fuel injected and hence the heat released.
Equations solved	Mass, momentum, energy, species.	Mass, momentum, energy, mixture fraction, species.
Physics of combustion modeled	Energy and product gas release only.	Energy and product gas release, plus simple combustion chemistry (fuel + air > product). In the more advanced models a separate sub-model for solid fuel pyrolysis is included.
Physics of fire suppression modeled	None modeled; the user must assume a change in heat release rate *a priori*.	This varies from no suppression (solid fuel pyrolysis rate specified) to including a solid fuel pyrolysis model. This is discussed further below.
Advantages	Simple model to implement; the modeler can be certain about the quantity of heat released.	The physics of combustion is more accurately captured; heat is released into the computational domain at locations where there are sufficient conditions to support flame (i.e. enough heat and oxygen).
Disadvantages	Peak temperatures achieved are dependent on the fire volume selected; temperatures can be too high or too low. Radiation heat transfer is greatly simplified or not modeled.	The model is more complex, potentially requiring more skill to assure correct application.
Use	Typically used for studying interaction of the smoke management system with heat and smoke from the fire.	As per volumetric models but also can be used for modeling physics associated with an FFFS.

3.5.1.1 Method 2: Mixing Controlled without Solid Pyrolysis

Description: This is the simplest and most well-established method of modeling combustion with the mixing controlled model. The user specifies *a priori* the heat released from a fuel surface per unit area. The CFD model determines the quantity of fuel to inject based on the fuel chemistry specified. Heat is released once this fuel meets sufficient air and heat.

Advantages: This is relatively straightforward, well-established, and validated approach.

Disadvantages: The method doesn't allow for any FFFS impact on the combustion process or fire spread, possibly leading to overly conservative outcomes.

FFFS effects: Allows for cooling by FFFS of the gas phase and on surrounding structures but it does not capture fire spread to adjacent fuel targets or the impact of FFFS on the combustion process and fire heat release rate. This technique could be used to assess the potential for an FFFS to provide savings on the ventilation system or structural protection.

Other notes: This method of combustion modeling can be used in more complex models described below to specify the pilot flame used for ignition of the fuel source. This method sees widespread use in the industry.

Example reference: *Capability of a CFD Tool for Assessing a Water Mist System in a Tunnel*, E. Blanchard, P. Boulet, and P. Carlotti [72].

3.5.1.2 Method 3: Mixing Controlled without Solid Pyrolysis with Fire Spread by Ignition of a Target

Description: This approach is the same as Method 2 except that adjacent fuel targets are now included. If the fuel reaches a specified temperature it will ignite and release an *a priori* specified amount of heat.

Advantages: As per Method 2, plus this method needs material properties which are reasonably easy to obtain (density, conductivity, heat capacity, ignition temperature). It is possible to capture the effects of an FFFS on fire spread.

Disadvantages: The method doesn't allow for any FFFS impact on the combustion process; once the fire spreads to materials they burn regardless of the application of water.

FFFS effects: Allows for cooling of the gas phase and on surrounding structures; it can inhibit the heat transfer process responsible for fire spread to adjacent targets. This technique could be used to assess the potential for an FFFS to provide savings on the ventilation system or structural protection, and could assist with demonstration of the ability of an FFFS to prevent fire spread.

Other notes: This method of combustion modeling can give outcomes highly dependent on the arrangement of fuel targets and pilot flames. This method is not widely used in the industry.

Example reference: *Calibrating an FDS Simulation of Goods Vehicle Fire Growth in a Tunnel Using the Runehamar Experiment*, M. Cheong, M. Spearpoint, and C. Fleischmann [73].

3.5.1.3 Method 4: Mixing Controlled without Solid Pyrolysis, Fire Spread by Ignition of a Target

Description: This approach is the same as Method 3 above except that an empirical extinction parameter is included. If the water reaches a burning surface the fire heat release rate will be reduced in proportion to the quantity of water reaching the surface.

Advantages: As per Method 3, plus this method allows for some suppression effects to be included.

Disadvantages: The method allows for FFFS impact on the combustion process; however, it is an entirely empirical approach which relies on water reaching the burning surface. There is no mechanism included which allows for gas phase cooling interrupting combustion. This means that once the fire becomes sufficiently large all water evaporates before it reaches the burning surface; therefore, no water can reach the burning surface and the impact of the FFFS isn't captured.

FFFS effects: As per Method 3 and this method allows for reduction of the fire heat release rate if the fire size is not too large. This technique can be used to assess the potential for the FFFS to limit the fire size. A drawback is that it can over predict the fire size; however, this at least would lead to conservative outcomes from a design perspective.

Other notes: This method of combustion modeling can give outcomes highly dependent on the arrangement of fuel targets and pilot flames, and the timing of FFFS activation. The method is not widely used in industry, though it could see more use as validation improves.

Example reference: *Numerical Simulations on the Performance of Waterbased Fire Suppression Systems*, J. Vaari, S. Hostikka, T. Sikanen, and A. Paajanen [74].

3.5.1.4 Method 5: Mixing Controlled with Solid Pyrolysis

Description: The disadvantages of Method 4 can be overcome by modeling the solid fuel heating up and undergoing pyrolysis reactions. The amount of Z=1 (fuel) injected into the domain depends on, and changes with, the heat feedback to the pyrolysis surface.

Advantages: The method is like Method 4 above but it allows for the complete energy balance taking place at a combustion surface to be modeled and interrupted by the FFFS.

Disadvantages: Pyrolysis is a complicated phenomenon which occurs on the surface of a burning material and within the material. The material moisture content and porosity can affect pyrolysis. Material properties for pyrolysis models tend to be difficult to measure, or they are better suited to laboratory scale applications. The pyrolysis process also takes place at small length scales where it may be impractical to model using CFD.

FFFS effects: As per Method 4 and allows for reduction of the fire heat release rate due to water reaching the burning surface or cooling surrounding gas.

Other notes: While this method of combustion and suppression modeling is the most physically realistic it is also the most complex. It can give outcomes highly dependent on the arrangement of fuel targets and pilot flames. Using this method of modeling for design purposes is a maturing field and more research into model development and validation is needed. However, like Method 4 above, this technique is expected to see more use as knowledge improves.

Example reference: *Fire Dynamics Simulator (FDS) Pyrolysis Model Analysis of Heavy Goods Vehicle Fires in Road Tunnels,* X. Wang [75].

3.5.2 Model Calibration with Experimental Data

CFD can model some aspects of fire suppression, and investigations have been conducted into water application rate effects [76] [11]. The field of CFD is not advanced enough to make deterministic predictions of water application rate and the resultant FHRR, but studies have revealed some insights that are likely to be improved on as tests and models improve. For instance, a study looking at a specific type of fire and configuration showed the following relative to a calibrated based case CFD model [76]:

- **0.06 gpm/ft^2 (2 mm/min).** Water application rates of 0.06 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.

The VTT Technology Research Centre performed a three-year long research project studying water spray dynamics to improve the capabilities of Fire Dynamics Simulator (FDS) [74]. Extensive modeling studied the cooling performance and flame suppression capabilities of FDS, all of which was validated with experimental data. The research conducted included simulating a small-scale fire, and then the full-scale experiments from the Runehamar and San Pedro de Anes tunnels.

The small-scale fire test modeled consisted of 20 wood pallets ignited by a 100 kW propane burner pilot flame. The fuel load modeled was simplified to 16 fuel packages measuring 0.3 m x 1.2 m x 0.1 m. The heat release rate data used was based on cone calorimeter data. This case showed that a simplified heat release rate curve best matched experimental data from burning wood pallets. Small-scale tests, again burning wood pallets, were also used to investigate the ability of CFD to model fire suppression by FFFS [74]. The method of modeling combustion was as per method 4 from Section 3.5.1.3.

These small-scale calibrations were then input to full-scale CFD models of one of the Runehamar fire tests without FFFS. Modeling the full Runehamar tunnel length of 800 m produced instabilities in the model, so a shorter 120 m segment was used. The results showed the CFD model well approximated the peak FHRR of 200 MW. Models were conducted for the FFFS operation also and although some differences in fire growth rate were observed, the model could show the ability of the FFFS to contain the fire growth rate.

CFD simulations by Nmira et al. [77] used a tunnel 25 m long, 3 m high, and 5 m wide with a single nozzle located slightly upstream of the fire. The fire was based on a polymer fuel burning with a potential unsuppressed FHRR of around 1 MW. The simulations focused on the effects of droplet size and water flow rate. For droplets between 25 and 100 µm diameter, the varying of water flow rate between 0.06 and 0.14 kg/s did not significantly change the burning rate or normalized temperatures. A significant decrease in temperature and burning rate was observed for 25 µm droplets when the flow rate was increased from 0.02 to 0.06 kg/s. The simulations also showed that larger longitudinal velocities resulted in higher evaporation rates and lower normalized temperatures. The analysis documented spray patterns as well.

Mist systems were also investigated by Iannantuoni et al. [78] using the software OpenFOAM. This research focused on spray pattern modeling. They first conducted experiments to measure the nozzle droplet diameter distributions at various working pressures. These were then compared to distributions and spray patterns produced in CFD. The simulations showed good correlation of droplet velocity and size with experiments.

Work by Sikanen et al. [79] evaluated the ability of different CFD turbulence models to model mist spray. Specifically, single and multi-orifice spray heads were used and compared to experimental data. It was concluded that the dynamic Smagorinsky turbulence model (a large eddy simulation) produced the best results, but the results are heavily affected by grid resolution. The authors noted that the grid resolution used may be too fine for use in design applications. The work also investigated the aerodynamic effects of droplets on each other, concluding that the drag reduction due to droplet interaction was very minor.

3.6 Fire Incidents

A summary of a few key incidents to highlight the role of FFFS during a real events is provided below. 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 [80].

3.6.1 Burnley Tunnel Fire 2007

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 [81]. A series of explosions (deflagrations) and fires occurred, in part 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 [81]. Ruptured fuel tanks were believed to contribute to the rapid fire growth [81]. Emergency ventilation and the FFFS were activated about two minutes after the fire ignition [10].

Three people were killed in this incident. All people suffered serious physical injuries because of the initial collisions, and two of the three deaths were a result of the effects of the fire [80]. The incident investigation report noted that FFFS cannot protect people inside a vehicle on fire because the fire is shielded and there is no way for water to reach the fire [81]. While the FFFS did not extinguish the fires, the fires were kept small enough to allow emergency services to intervene and there was limited damage to the structure. The Burnley Tunnel reopened to traffic only three days after the incident. In contrast, after the Mont Blanc Tunnel fire, which was similar in terms of the primary fire vehicle, the tunnel remained closed for three years [81].

The Burnley Tunnel fire confirmed that FFFS performance is consistent with observations made in theoretical research and controlled tests, and clearly demonstrated the potential benefits of 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 FFFS.

One recommendation arising from the report was that computer control systems for FPLS features be regularly tested and where necessary upgraded. This recommendation was based on observations of the high demand placed on control systems during the emergency, which had potential to delay an operator's response time and effectiveness [81].

3.6.2 Minor Incidents Involving FFFS

Miscellaneous minor incidents are reviewed below.

- **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 [82].
- **Airport Link Tunnel, Brisbane, Australia, 2015.** A small van caught fire, sprinklers were activated, and fire brigade crews extinguished the fire relatively quickly [83].
- **Airport Link Tunnel, Brisbane, Australia, March 2015.** A blown tire on a truck started a small fire. The FFFS were used during the incident, which was cleared in just over one hour [84].
- **M5 East Tunnel, Sydney, Australia, 2014.** A car fire was reported and the tunnel's sprinkler system suppressed the fire to a controllable level before fire fighters made their way to the scene [85].
- **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 [86].
- **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 [87].

3.7 Summary

Questions raised in the introduction are outlined below, along with comments on the findings of the literature survey and synthesis.

- ***What are the design FHRRs recommended?***
  NFPA 502 states that a representative FHRR for an HGV is 150 MW, and a flammable liquid tanker is 300 MW. These values should be used only as a starting point in determining the design FHRR for a given tunnel. The final determination of the design fire should be made after considering all relevant factors (e.g. tunnel geometry, traffic makeup, facility risk, etc.).
- ***What is the impact of FFFS on FHRR?***
  The expected impact of FFFS varies with system type, application rate, droplet size, and nozzle type. However, various small and full-scale tests indicate that a reduction in peak FHRR of 50 to 70% is likely (assuming prompt activation of the system and a water application rate of 0.15 to 0.20 gpm/ft^2 [6 to 8 mm/min]) [1] [2] [3] [4]. Information on nozzle type and impacts on the FHRR could be better documented and this is an area where further research would be beneficial. Laboratory scale testing has shown that FFFS only reduces the FHRR for liquid fuel spills if an AFFF is added [5].

- ***How do different types of FFFS and their activation and application rates affect the fire?***
  Droplet diameter varies between deluge and mist systems. Mist systems tend to provide greater temperature reduction, but deluge systems have a greater ability of reaching and cooling the burning surface. Water mist droplets are unable to penetrate the fire plume and reach the seat of the fire. For shielded fires water spray cannot reach the seat of the fire and thus performance is similar between deluge and mist.

  Delayed activation of FFFS limits the reduction in peak FHRR achieved [6]. Typically, a higher water application rate results in a slightly lower peak FHRR [2] [3]. However, for deluge system water application rates of 0.15 gpm/ft^2 (6 mm/min) and greater, the difference in peak FHRR (e.g. between 0.15 gpm/ft^2 and 0.20 gpm/ft^2) is small and unlikely to be of significance for integrated FFFS-EVS designs

- ***What is the role of laboratory scale testing and full-scale testing?***
  Combustion modeling remains a heavily researched topic, and the full physics of combustion are not completely understood. Generating experimental data in full and small-scale tests allows theories to be tested, CFD models to be calibrated, and other practical insights to be gained about how fires burn in tunnels.

- ***What is the role of CFD modeling?***
  CFD models are a relatively quick and cost effective means of investigating a particular fire scenario in a tunnel where the FHRR is specified a priori. CFD can be reliably used to predict gas phase cooling. However, for FHRR or fire spread prediction, in order to draw any useful conclusions from a model, it must be calibrated against experimental data. CFD also has a limited ability to model certain aspects of FFFS in tunnels (e.g. FFFS interruption of the combustion/pyrolysis process).

4 FFFS DESIGN AND PERFORMANCE

In this section the performance objectives of FFFS in road tunnel applications are discussed. Discussion is provided on best practices and design considerations for road tunnel FFFS application including: hydraulic analysis, system configuration, functioning components, system operation, and system maintenance.

4.1 FFFS Overview

Fires in road tunnels present a unique challenge in the design of fire protection systems, both to traditional fire fighting strategies and to the thermal protection of these facilities. The closed geometry of a road tunnel confines the heat and combustion products, preventing easy dispersal. Large volumes of smoke and other hazardous products are produced which can pose a threat to motorists. Smoke also obscures visibility and limits access for rescue and fire fighting personnel.

In the enclosed confines of a road tunnel, high convective and radiative heat levels can cause fires to spread to other vehicles. Heavy goods vehicles (HGVs) such as semi-trailer trucks regularly carry large amounts of flammable cargo that, once ignited, can result in catastrophic tunnel fires. The extreme temperatures generated in large fires such as these can cause severe damage to tunnel structures resulting in extended closures for repairs.

Because of the continuously changing variety of vehicles and cargoes passing through a highway tunnel, FFFS should be able to provide effective suppression and control of fires with varying fuel types, geometries, and shielding conditions. The design of FFFS must consider the fuel content associated with the type and quantity of cargo that are allowed passage in the tunnel and the extent of protection expected from the FFFS. Determining the performance objective of the FFFS involves consideration of several factors unique to the facility, including:

- Tunnel length and geometry (cross section, fire geometry, passive protection).
- Traffic type and volume.
- Life-safety considerations and systems.
- Availability of emergency response and water.
- Socio-economic factors associated with an extended tunnel closure.
- Structural vulnerability of the tunnel (e.g. submersed tubes).

4.2 NFPA 502 Overview

The North American standard for FFFS in road tunnels is NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways [12]. NFPA 502 establishes FFFS performance objectives and identifies specific requirements unique to road tunnels that must be considered in the analysis and design of FFFS.

4.2.1 Categorization of FFFS

NFPA 502 [12] summarizes the objectives of FFFS into four performance categories: fire suppression, fire control, volume cooling, and surface cooling. The objectives for each category are summarized in Table 4-1 (reproduced from NFPA 502 Section 9.2). The category selected will directly affect key FFFS design parameters such as water application rate, droplet properties, nozzle design and layout, water supply, water additives, fire alarm, system controls, and activation response time. The objectives of some categories will overlap, as the categories follow a tiered approach (e.g. fire control is volume cooling with the added goal of reducing the FHRR).

Table 4-1: FFFS design categories.

System	NFPA 502 objective	Pros	Cons
Fire suppression	Designed to sharply reduce the heat release rate of a fire and prevent its growth by means of direct and sufficient application of extinguishing agent through the fire plume to the burning fuel surface.	Potential for meeting life safety goals with larger design fires.	Needs a large volume of water. Many vehicle fires are shielded and water cannot be directly applied
Fire control	Designed to limit the size of a fire by distribution of extinguishing agent to decrease the heat release rate and pre-wet adjacent combustibles while controlling gas temperatures to avoid structural damage.	Potential for meeting life safety goals with larger design fires.	Needs a large volume of water.
Volume cooling	Designed to provide substantial cooling of products of combustion but is not intended to affect heat release rate directly.	Potential use of mist systems, which reduces water demand requirements.	No reduction in FHRR; may not allow for large design fire.
Surface cooling	Designed to provide direct cooling of critical structure, equipment, or appurtenances without directly affecting heat release rate.	May be useful where additional surface cooling is needed to handle very large fires (e.g. tanker fires).	Little to no reduction in FHRR or gas phase cooling. Large piping systems and volume of water needed. No known examples in tunnels.

4.2.2 NFPA 13 Compliance

NFPA 502 requires conformance to NFPA 13, Standard for the Installation of Sprinkler Systems [88] for material properties, hydraulic performance, functional provisions for fire department interaction, system approval, etc. NFPA 13 specifies most requirements based on occupancy classification. Because the standard was developed for buildings and facilities, certain provisions may not be directly applicable to road tunnels. It is left to the system designer to fully understand and apply all requirements of the standards and applicable local codes when developing a tunnel FFFS. Other referenced NFPA publications may be applicable based on the type of FFFS selected (refer to Section 4.3).

Per NFPA 13, materials used in the construction of FFFS must listed for use in fire protection systems. If exceptions are needed for any component, they must be submitted to the permitting authority for approval. Further discussion on FFFS components is given in Section 4.6.

4.2.3 NPFA 502 Design Requirements

A summary of what are considered the most critical NFPA 502 requirements for FFFS is presented in Table 4-2; the standard should be referred to for the full set of requirements.

Table 4-2: NFPA 502 Chapter 9 requirements [12].

NFPA 502	Extract	Comment
9.1.2	When a fixed water-based fire-fighting system(s) is installed in road tunnels, it shall be installed, inspected, and maintained in accordance with NFPA 11, NFPA 13, NFPA 15, NFPA 16, NFPA 18, NFPA 18A, NFPA 25, NFPA 750, or other equivalent international standard.	Compliance with NFPA 13 is further discussed in Section 4.2.2.
9.2.1	The goal of a fixed water-based fire-fighting system shall be to slow, stop, or reverse the rate of fire growth or otherwise mitigate the impact of fire to improve tenability for tunnel occupants during a fire condition, enhance the ability of first responders to aid in evacuation and engage in manual fire-fighting activities, and/or protect the major structural elements of a tunnel.	These are the fundemental performance requirements of a road tunnel FFFS. Design approach to achieve the goals are discussed in this section. Structural protection is addressed in Section 6.
9.2.2	Fixed water-based fire-fighting systems shall be categorized based upon their desired performance objective in 9.2.2.1 through 9.2.2.4.	These four categories are presented and discussed in Table 4-1.
9.3.3	System components shall be listed or as approved by the AHJ.	System components are discussed in Section 4.6.
9.3.4.1	For the sizing of the emergency ventilation system in accordance with Section 11.4, the effect of the fixed water-based fire-fighting system shall be taken into account.	Ventilation impacts are discussed in Section 5.
9.3.4.2	For protection of structural elements, the applicable provisions of Section 7.3 shall apply unless evidence of the performance of the required structural fire protection by a fixed water-based fire-fighting system is provided and approved by the AHJ.	Structural fire protection impacts are discussed in Section 6.
9.4.2	The tunnel geometry (width, ceiling height, obstruction location) shall be considered when selecting such parameters as nozzle location and nozzle positioning.	FFFS zone design is addressed in Section 4.5.1.
9.4.4	A fire hazard analysis shall be conducted to determine both the design parameters of the water based fire-fighting system and the type of detection and activation scheme employed. The water-based fire-fighting system shall address the anticipated vehicle types and contents, ease of ignition and re-ignition of the fuel, anticipated fire growth rate, and difficulty of achieving one or more of the performance objectives established in Section 9.2 or as otherwise acceptable to the AHJ.	Design parameters are discussed in Section 4. Detection is addressed in Section 4.7. Hazard mitigation (FHRR impact) is discussed in Section 3.
9.4.5	The presence of obstructions and the potential for shielding of water-based fire-fighting system discharge shall be addressed to ensure that system performance is not affected.	Shielding of the fuel load prevents large droplets from reaching the combustibles and can limit the effectiveness of FFFS. Tests with shielded and unshielded fires have been conducted (refer to Section 3).
9.4.6	The range of ambient conditions that could be experienced in the tunnel shall be identified.	The potential for freezing should be addressed in the design.

NFPA 502	Extract	Comment
9.6.1	When a fixed water-based fire-fighting system is included in the design of a road tunnel, the impact of this system on other measures that are part of the overall safety concept shall be evaluated. At a minimum, this evaluation shall address the following: 1) Impact on drainage requirements 2) Impact on tenability, including the following: a. Increase in humidity b. Reduction (if any) in stratification and visibility 3) Integration with other tunnel systems, including the following: a. Fire detection and alarm system b. Tunnel ventilation system c. Traffic control and monitoring systems d. Visible emergency alarm notification 4) Incident command structure and procedures, including the following: a. Procedures for tunnel operators b. Procedures for first responders c. Tactical fire-fighting procedures 5) Protection and reliability of the fixed, water-based, fire fighting system, including the following: a. Impact events b. Seismic events c. Redundancy requirements 6) Ongoing system maintenance, periodic testing, and service requirements	Drainage is identified in Table 2-4. System integration is discussed in Section 4.7. Maintenance is discussed in Section 4.8. System reliability is discussed in Section 4.9. Testing has shown the positive impact of FFFS on tenability with respect to thermal conditions, refer to Section 3.4.3. Impact on incident command is considered in Section 4.7 and in separate references [15].
9.6.2	The engineering analysis shall also address delays in activation.	In addition to delays in system activation, the fill time for dry systems should also be considered

4.3 Design of Fixed Fire fighting Systems

FFFS in road tunnels are intended to provide water spray capability over select coverage areas (zones) of the tunnel roadway surface area. Delivery of water to each roadway zone is controlled by deluge valve. In response to a fire incident within the roadway, two or more adjacent zones may be activated to discharge water onto the coverage area. The FFFS must also provide fire department connections (FDCs) to allow the fire department to boost system pressure, if necessary.

To the extent practical, FFFS in road tunnels should incorporate standard fire suppression system components, piping, valves, and appurtenances. FFFS in road tunnels should be designed with careful consideration of maintenance requirements and ease of access for testing and inspection. Hydraulic calculations must be developed in accordance with the applicable standards (e.g. NFPA 13) to demonstrate that water flow and pressure to be delivered to the roadway is sufficient quantity to meet system demand requirements.

While there are four main design categories of FFFS (addressed in Table 4-1), they all involve a combination of pipework, nozzles, and valves. There is some variation in system components available, which falls into three main categories of physical installation. These are given in Table 4-3.

Table 4-3: Types of FFFS.

System	Description	Pros	Cons
Deluge	Deluge sprinkler systems discharge water through a system of open spray nozzles simultaneously over a given coverage zone. Control of the deluge valve is typically automatic or semi-automatic responding to inputs from a fire detection system or other form of incident alert.	Deluge systems are advantageous for tunnels because they can provide rapid application of high volumes of water or extinguishing agent directly to the fire. They pre-wet combustible materials at distance from the seat of the fire and prevent the spread of fire.	Zone actuation is limited to two or three zones at any given time to avoid excess water pressure drop at the incident zone.
Mist	A variant of traditional deluge systems, but using nozzles capable of delivering small droplets (50 to 400 microns).	Small droplets are more easily vaporized, better cooling the combustion products. Lower water application rate needed for cooling when compared to standard deluge systems.	High pressure pumps and piping networks needed. Pipework materials are typically required to be stainless steel to prevent corrosion and subsequent debris blockage. Many systems are proprietary and therefore all parts must be purchased from the one manufacturer for the life of the system. Systems are also more complex because of higher pressures, need for filters, etc. Water application potentially adversely affected by ventilation due to smaller droplets; thus, ability to reduce FHRR may be limited.
Aqueous film forming foam (AFFF)	Deluge or mist system where a foam additive is injected into the water stream. The discharge is a mixture of foam laden water in prescribed concentration intended to cover the combustible material with a fine layer of foam. AFFF systems are intended primarily to combat flammable liquid fires and are generally found only in tunnels that allow bulk transport of these cargoes.	They are purportedly effective in combatting liquid fuel fires when the fuel is distributed evenly on the ground surface [5].	AFFF systems are potentially costlier to install and need more maintenance. They offer no real advantage in non-flammable liquid fires. Their practical effectiveness for highway tunnel applications is still being researched.

Based on the type of FFFS used, additional NFPA publications may also be applicable and should be used where appropriate:

- NFPA 15 Standard for Water Spray Fixed Systems for Fire Protection
- NFPA 16 Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems
- NFPA 750 Standard on Water Mist Fire Protection Systems

4.4 Water Application Rate

Road tunnel FFFS involves a substantial amount of water provided over an extended period (designs are frequently provided to deliver water for a time in the order of at least 60 minutes). This can place a significant burden on the available water supply, delivery networks, and drainage systems. The FFFS water application rate must be carefully considered relative to the objectives for exposure protection, control of burning, suppression, and extinguishment.

NFPA 502 does not state water application standards for tunnel FFFS. Rates used in U.S. highway tunnels have been based on international standards, largely Japanese and Australian, results of full-scale tunnel test programs, and with consideration of the requirements of NFPA 13. To date, most U.S. road tunnels that have been equipped with FFFS use water application rates between 0.15 gpm/ft^2 and 0.20 gpm/ft^2 (6 mm/min to 8 mm/min) The recently opened SR 99 Tunnel in Seattle WA selected a water application rate of 0.30 gpm/ft^2 (12 mm/min) for its FFFS.

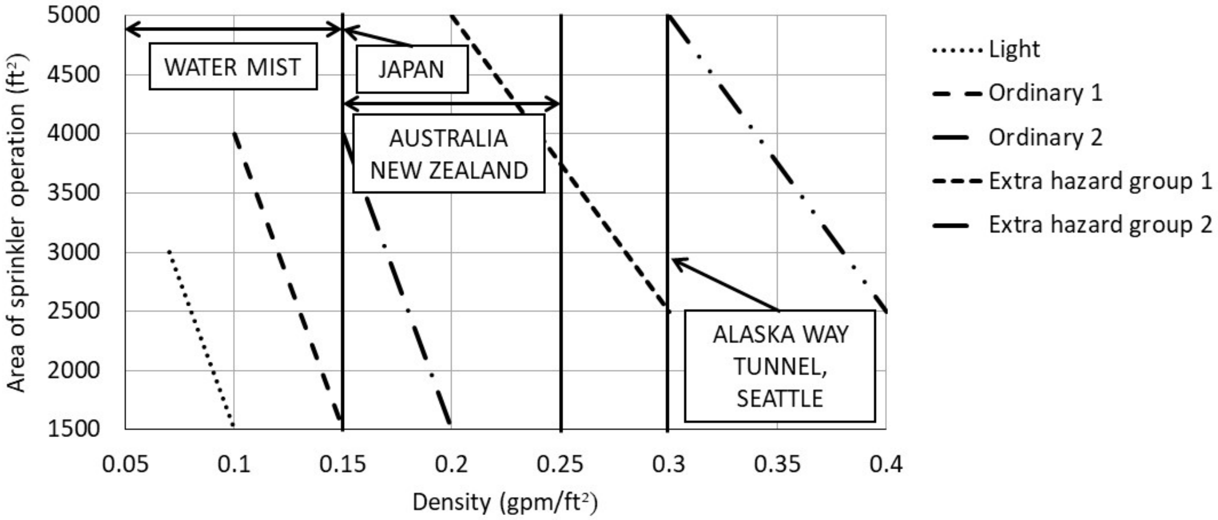


Figure 4-1: Graph. Water application rates (per NFPA 13 Figure 19.3.3.1.1) with common road tunnel applications indicated [88] [15].

Japan and Australia have required FFFS in their road tunnels for many decades. Japan generally requires that tunnels to be equipped with systems that deliver 0.15 gpm/ft^2 (6 mm/min) (tunnels in Japan are required to have an FFFS based on length and traffic volume). In Japan, many full-scale tests were conducted, however, the tests were conducted several years ago and available details are limited [10]. One recent paper describes some of the model scale testing conducted as a basis for the water application rate, with full-scale testing only been conducted as a confirmation test in the completed facility [89]. Test reports citied in this work are from the 1960s. Recent data on fires and FFFS activation in Japan has also been collected [89].

The Australian standard for water application rate is 0.18 gpm/ft^2 to 0.25 gpm/ft^2. Tests with FFFS in tunnels were not carried out to confirm the water application rate range used. Sydney Harbor Tunnel was the first Australian tunnel to be provided with FFFS and the water application rate was 0.25 gpm/ft^2 (10 mm/min). The process to determine this water application rate relied on the sprinkler standard AS 2118. The tunnel was treated as a storage area under AS 2118; two trucks side by side with a height of 14.8 ft. (4.5 m) were construed to represent a storage commodity and classified as extra high hazard category 2, which required a water application rate of 0.25 gpm/ft^2 (10 mm/min) over an area of 2800 ft^2 (260 m^2) [90]. It was also noted that NFPA sprinkler tests were conducted at comparable water flow rates and that the fire was not fully extinguished; thus, the system was installed on a basis that it would suppress but not extinguish the fire. This behavior of the system has been observed in practice [15]. A recent review of all tunnel fires in Australia from 1992 to 2017 identified 78 total fires, and deluge was deployed in 30 of the instances [91]. The review noted that in cases where the deluge system was used, 90% of fires were extinguished within 30 minutes and tunnels were reopened to traffic in an average of 74 minutes.

The determination of appropriate water application rate and the effectiveness of FFFS in controlling tunnel fires has been an area of active research in recent years. The results of this research are described in previous sections of this document. In some studies, full-scale fire scenarios were created in tunnel environments and the effective FHRR reduction was measured relative to water application rate. The studies consistently showed good performance at water application rates consistent with U.S. practice. A survey of water application rate, including relevant test programs and installation examples, is provided in Table 4-4.

Table 4-4: Survey of water application rates [15].

Application rate	Test programs	Examples	Standards
0.30 gpm/ft^2 **(12 mm/min)**	LTA tests [4]: Potential FHRR of 511.8 MBtu/hr (150 MW) was restricted to less than 170.6 MBtu/hr (50 MW). LTA tests [4]: 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 [92]: 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 [93]	AS 2118.3 [94]: 0.31 gpm/ft^2 (12.5 mm/min), nitrocellulose manufacturers NFPA 15 [95]: For extinguishment requires 0.15 gpm/ft^2 (6 mm/min) to 0.50 gpm/ft^2 (20.4 mm/min) NFPA 13 [88]: Allows 0.3 to 0.2 gpm/ft^2 (12 mm/min to 10 mm/min depending on area of application) for an aircraft hangar (Extra Hazard, Group 1)
0.25 gpm/ft^2 **(10 mm/min)**	Sydney Harbor Tunnel [96]: 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. See also [90]. Arvidson [6]: 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 suppression once the fire burned through the shield. Runehamar 2013/2016 tests [3] [2]: shielded fire with an application rate of 0.25 gpm/ft^2. FHRR reduced by 50% or more.	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 [86]: A car caught fire and was fully alight by the time FFFS was activated. The FFFS quickly controlled the fire.	AS 2118.3 [94]: Ammunition filling plants, explosives manufacturing, fireworks manufacturing, tar distillers NFPA 15 [95]: Not less than 0.26 gpm/ft^2 (10.2 mm/min) for exposure protection NFPA 13 [88]: Allows 0.3 to 0.2 gpm/ft^2 (12 mm/min to 10 mm/min depending on area of application) for an aircraft hangar (Extra Hazard, Group 1)

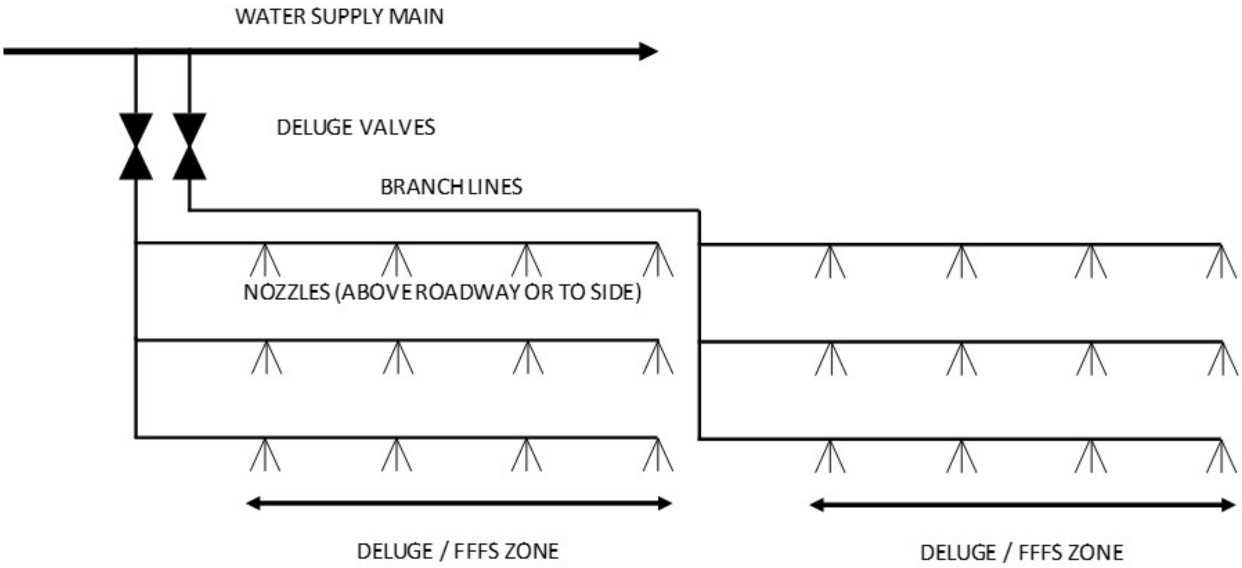
Application rate	Test programs	Examples	Standards
0.20 gpm/ft^2 **(8 mm/min)**	LTA [4]: Potential FHRR of 511.8 MBtu/hr (150 MW) was restricted to less than 170.6 MBtu/hr (50 MW).	Port of Miami Tunnel. Tunnels with 0.18 gpm/ft^2 (7.5 mm/min): Burnley Tunnel, Melbourne, Australia. Burnley Incident, 2007 [80] [81]: 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.	NFPA 13 [88]: Allows 0.2 to 0.15 gpm/ft^2 (8 to 6 mm/min depending on area of application) for a library with stacked books (Ordinary Hazard, Group 2)
0.15 gpm/ft^2 to 0.16 gpm/ft^2 **(6 mm/min to 6.5 mm/min)**	Arvidson [6]: 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 [97]: 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. Runehamar 2016 tests [2]: water application rate of 0.12 to 0.21 gpm/ft^2 kept FHRR at less than 30 MW (potential unsuppressed FHRR of 80 MW).	Midtown Tunnel, Norfolk, VA (0.17 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 [97]. Sprinklers have been included in Japanese road tunnels since at least the 1970s [97].	NFPA 13 [88]: Allows 0.15 to 0.10 gpm/ft^2 (6 to 4 mm/min depending on area of application) for an automobile parking location (Ordinary Hazard, Group 1)

Application rate	Test programs	Examples	Standards
<0.15 gpm/ft^2 (<6 mm/min)	A water mist system was tested with a water application rate of 0.09 gpm/ft^2 (3.6 mm/min). The FHRR was approaching 68.2 MBtu/hr (20 MW) when then FFFS was activated, and after this time the FHRR was gradually reduced to less than 10 MW after 8 to 10 minutes. Temperatures 45 m downstream of the fire were reduced from 200 °C to less than 50 °C [98]. A low pressure mist system was tested at 0.05 gpm/ft^2 (2.2 mm/min) and kept the FHRR to 59 MW relative to a potential FHRR in excess of 200 MW. An application rate of 0.13 gpm/ft^2 (5.2 mm/min) kept the FHRR to 46 MW (same fuel load) [68].	Tunnels with less than 0.10 gpm/ft^2 (6 mm/min): Kemp Place, Brisbane, Australia (sprinklers)	NFPA 13 [88]: Allows 0.15 to 0.10 gpm/ft^2 (6 to 4 mm/min depending on area of application) for an automobile parking location (Ordinary Hazard, Group 1) NFPA 750 [99] : Does not specify a water application rate and instead requires systems to be used only for the listed applications; performance objectives include control, suppression or extinguishment.

4.5 Fixed Fire Fighting System Configuration

4.5.1 Zone Configuration

The length and number of zones should be considered to determine the available water supply and area of coverage. Standard practice is to provide a minimum of two zones operating so that a fire incident occurring near a zone boundary can be effectively addressed by the system. A single fire incident is generally considered to cover a length of around 75 ft. This is based on the maximum length of single cargo trailers on U.S. roadways. Minimum sprinkler coverage capacity is typically in the range of 100 to 150 feet. This can be achieved by the provision of any number of zones with total length of up to 150 feet. It is general practice to limit zone length to 100 feet. This provides the minimum total coverage while also limiting the number of deluge valves.



Source: FHWA

Figure 4-2: Typical FFFS zone arrangement [15].

4.5.2 System Water Demand

The FFFS must deliver the minimum water application rate for all possible zone discharge scenarios over the number of available zones. The minimum residual pressure needed at the water supply connection is calculated based on elevation and frictional pressure losses through the piping network, as well as the minimum design (listed) pressure at all nozzles. The total water supply demand should account for overspray as nozzles nearer their respective deluge valves will draw more water than more remote nozzles due to differential in pressure. Once the water demand and pressure requirement are determined, the designer can evaluate an acceptable water supply option.

A typical tunnel FFFS will draw in the range of 2000 gpm to 4000 gpm. Standpipe demand may be required to be added to the deluge demand. This will depend on fire department requirements.

4.6 FFFS Materials and Piping Network Design

4.6.1 Supply Piping Configuration

At least one permanent water supply is required by NFPA 13. Two supply mains from separate utility connections may be required depending on system demand. Sizing of the main header and zone branch piping should consider overall hydraulic pressure losses. It may advantageous to provide a larger header pipe with smaller branch piping or vice-versa. The FFFS main is ideally run along the roadway either underground or overhead. Piping from the utility connection up to deluge valves is usually wet. If freeze protection is necessary, the pipe may be buried or provided with an active freeze protection system (e.g. heat tracing and insulation, or a looped and heated circulation system).

All sections of dry piping should be sloped to allow for proper drainage. Failure to drain the system increases the potential for corrosion and freeze issues. The system can be drained either at automatic drain valves or through pendent nozzles. All system piping, including water supply, must be routed and appropriately supported and protected in accordance with the provisions of NFPA 13. Isolation valves must also be provided with supervisory devices for maintenance.

4.6.2 Over-Height Vehicle Protection

Over-height vehicles can cause serious damage to ceiling mounted systems; even vehicles under the posted clearance can be problematic (e.g. flapping tarps or unsecure loads) [100]. Over-height warnings and sometimes barriers are possible solutions. There is also the option of using sidewall mounted nozzles and piping. This puts the piping over the roadway shoulders but out of the travel lane area. Japanese tunnels use sidewall nozzles [97].

4.6.3 Deluge Valves

Deluge valves will be located either within deluge valve cabinets, in utility corridors, or in other protected locations. Each valve serves a single deluge zone. After a fire incident or testing, the zone riser should automatically drain via a drainage mechanism internal to the valve. Deluge valves should be located as near to their respective zones as practical. They are commonly located in dedicated valve cabinets along the roadway or in utility corridors when available. Figure 4-3 shows a typical tunnel deluge valve cabinet.

Source: FHWA

Figure 4-3: Deluge valve cabinet arrangement [15].

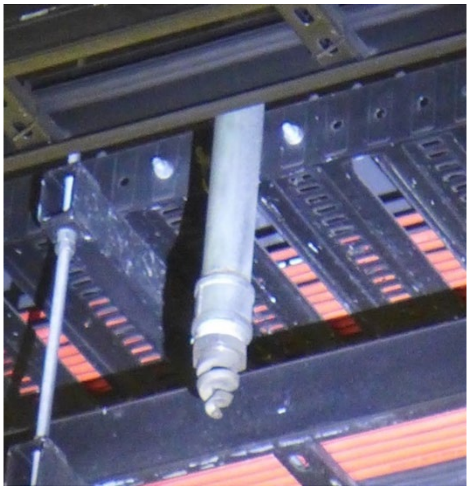
In non-tunnel deluge system applications, the deluge valve is commonly remotely opened but must be manually closed at the valve. In tunnel systems, accurate identification of the fire location can be difficult. If zones selected for activation are incorrect, then they must be de-activated before the correct ones can be activated. For tunnel applications, it is preferred that deluge valves can be both opened and closed remotely. An operator at the operation control center or emergency personnel at the FACP must be able to de-activate zones as needed during an incident.

Each deluge valve assembly should be equipped with an isolation valve and flow test connection just downstream of the deluge valve. This allows testing of the FFFS up to the deluge valve without requiring that water be discharged onto the roadway. Piping downstream of deluge valves cannot be tested in this manner. Periodic testing with water discharge to the roadway is conducted in several tunnels [15].

4.6.4 Deluge Nozzles

FFFS deluge nozzles (sprinkler heads) may be off-the-shelf types as described in NFPA 13 or specialty nozzle types designed specifically for deluge systems. Listed nozzles must be used according to their listed coverage area and pressure requirements. AHJ approval is typically required for any unlisted products.

Nozzles may be either standard or extended coverage. Extended coverage nozzles can minimize overhead sprinkler piping in a congested tunnel ceiling area. The heads must be installed with the supplied fusible links removed to allow for deluge operation. The entire deluge system distribution piping network and nozzles must be located outside any vehicle clearance envelope. Figure 4-4 shows an example of a spiral nozzle, which is used in several road tunnels in New Zealand and Australia. Regular sprinkler nozzles, without the glass bulb, are also used (refer to Figure 4-5).



Source: FHWA

Figure 4-4: FFFS nozzle in the Mount Victoria Tunnel [15].

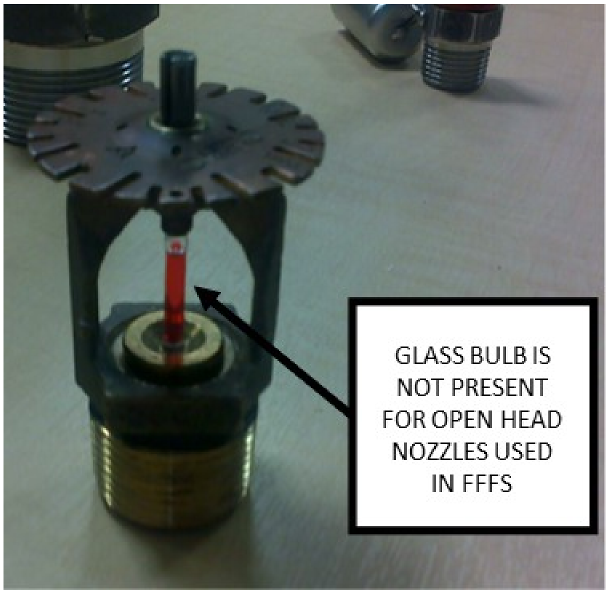


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Figure 4-5: FFFS nozzle example.

Nozzle spray patter data from manufacturers typically comprises the spray pattern distribution and nozzle K-factor [101]. The spray pattern distribution comes in the form of the conical output from the nozzle as well as the delivered water density at a given distance below the sprinkler and ceiling. These data can be used to help develop a validated model of a sprinkler system [102]. The droplet size distribution is not normally reported by nozzle manufacturers since the measurement of the distribution requires sophisticated imaging techniques to record the droplet sizes; techniques such as phase Doppler or laser diffraction probes are applied [103]. While it is not common for manufacturers to report droplet size distribution, test data are reported in literature that provide a range of droplet size diameters with respect to pressure (refer to Table 4-5).

The most critical parameters for FFFS effectiveness are the water application rate and droplet size; however, more research is needed to understand how these two parameters impact the integration of FFFS and EVS. Section 5 discusses the interaction between FFFS and critical velocity. Droplet diameter is a key parameter for cooling the environment, with smaller droplets providing more efficient cooling [70]. This would likely mean that smaller droplets reduce the critical velocity more than large droplets, however, at some point the droplets could become too small, such that they are just blown away by the tunnel air velocity and have little effectiveness [70]. Conversely large droplets might be more effective at penetrating the fire plume, however, this means that their cooling effects are less, unless the droplets reach the burning surface, which is difficult in a vehicle fire due to shielding. Research is needed to understand the balance between these factors.

Table 4-5: Droplet statistics with varying nozzles, pressures, and spray heights [103].

Spray nozzle	**Test pressure (bar)**	**Spray height (in.)**	**$D_{V0.5}$ (µm) (50% drops larger than this diameter)**	**$D_{V0.1}$ (µm) (10% drops smaller than this diameter)**	**$D_{V0.9}$ (µm) (90% drops smaller than this diameter)**	**D_{32} (µm) (Sauter mean diameter)**
Swirl type atomizer	68.9	15	0.0037” (95.2)	0.0022” (55.3)	0.0053” (134.7)	0.0036” (90.5)
Swirl type atomizer	68.9	24	0.0036” (90.6)	0.0017” (42.9)	0.0058” (146.3)	0.0031” (79.6)
Cluster swirl type atomizer	68.9	15	0.0034” (86.3)	0.0019” (47.2)	0.0050” (127.1)	0.0031” (78.4)
Cluster swirl type atomizer	68.9	24	0.0042” (107.1)	0.0020” (50.9)	0.0068” (172.3)	0.0036” (90.2)
Full cone nozzle	6.9	15	0.0132” (334.1)	0.0054” (136.2)	0.0237” (601.5)	0.0113” (286.5)
Full cone nozzle	6.9	24	0.0131” (332.6)	0.0054” (136.5)	0.0234” (594.1)	0.0117” (296.1)
Full cone nozzle	10.3	15	0.0117” (298.3)	0.0047” (120.1)	0.0215” (545.5)	0.0101” (256.5)
Full cone nozzle	10.3	24	0.0112” (284.5)	0.0049” (124.8)	0.0195” (495.5)	0.0101” (255.3)
Spiral nozzle	6.9	15	0.0060” (151.2)	0.0037” (93.1)	0.0081” (206.5)	0.0066” (168.2)
Spiral nozzle	6.9	24	0.0071” (179.5)	0.0047” (120.0)	0.0092” (234.1)	0.0070” (177.4)
Spiral nozzle	10.3	15	0.0062” (157.0)	0.0039” (98.8)	0.0083” (211.6)	0.0067” (170.1)
Spiral nozzle	10.3	24	0.0070” (177.9)	0.0048” (121.5)	0.0090” (228.3)	0.0071” (179.8)

4.7 System Integration with FFFS

4.7.1 Fixed Fire Fighting System Fire Detection and Controls

Control and activation of FFFS can be through several ways:

- Automatically via an automatic fire detection system
- Manually at a remote facility control location
- Manually at the deluge system control panel located near the tunnel
- Manually at the individual deluge valves

Automatic system activation and zone selection are provided by the fire alarm control system in conjunction with the fire detection system. NFPA 13 requires that system hardware used in the control of fire detection and suppression systems be listed specifically for use in fire protection systems. If non-listed devices are required, the AHJ should be consulted early in the design process and concurrence obtained. This typically occurs when an unlisted SCADA system is used to control the FLS systems, as opposed to a listed FACP. NFPA 72 [104] contains requirements for fire alarm initiating devices, including smoke and heat detectors, flame and smoke video detection, and gas detection. As prompt response by a tunnel operator or automatic systems is necessary, the means of fire detection should be carefully considered and tested for accuracy and reliability.

When a fire is detected at a specific location within the tunnel, the appropriate zone is identified and a preprogramed coverage zone(s) for that fire location is activated. The sequence of events leading to activation can vary and depend on whether the tunnel is monitored by an operator 24/7, part time, or unmonitored (typically with a local alarm). For properties that are monitored by the owner agency or contractor, proprietary supervising station requirements should be considered. For properties that are monitored by an outside agency, central station monitoring requirements should be followed.

In some instances, a back-up automatic activation system is provided to a main manual system. This typically uses a LHD to identify the fire location. The LHD would be an addressable sensing cable, which can detect absolute temperature or rate of rise, with each detection zone coincident with a specific FFFS zone. Experience from tunnel fires in Australia and New Zealand is that the LHD does not activate in an incident until the fire is at an advanced stage [15].

Flame and smoke sensing cameras have also been used for automatic detection of fire. Testing using fuel pan fires in the Seattle I-90 tunnels showed that for a simulated liquid fuel fire, cameras detected the fire an average of 33 s after ignition, with water from the FFFS reaching the fire at 125 s (FHRR at 41.5 MW based on a 20 MW/min growth rate for liquid fuels) [105]. For a simulated HGV fire, cameras detected the fire an average of 83 s after ignition, with water from the FFFS reaching the fire at 173 s (FHRR at 5.3 MW based on a HGV fire assumption). These tests demonstrated prompt activation using solely automatic means.

Commonly, an activation protocol known as positive alarm sequence as described in NFPA 72 [104] is used. The sequence describes a chain of events leading either to zone discharge or an abort if no fire is identified. The sequence takes the following form:

1. Fire detection system detects a fire and sends an alarm to the operator.
2. A countdown begins, during which the operator can acknowledge the alarm.
3. If acknowledged, the operator is given more time to confirm the fire and location via CCTV or abort the FFFS discharge.
4. If alarm is not acknowledged or countdown expires, the zone(s) identified by the fire detection system will discharge.
5. Any further activations by the detection system should not trigger additional zone activations.

The system must be programmed such that the operator can override an automated response if necessary. For example, in a tunnel heat will travel over a large number of FFFS zones and trip the LHD in zones remote from the incident. If all of these zones were to discharge water, there may not be enough water capacity available in the incident zone to suppress the fire (FFFS can be feasibly designed with enough water supply capacity to feed two or three zones). Conversely, the fire can propagate or the operator may need to correct their choice, which means the operator needs to have the ability to shut zones off and start others.

It should be noted that 24/7 monitoring of a facility needs a dedicated space and well trained staff. Two operators typically need to be on duty at all times to provide coverage during operator breaks. Example control rooms are shown in Figure 4-6 and Figure 4-7.

Source: FHWA

Figure 4-6: Sydney Harbor Tunnel control room [15].

Source: FHWA

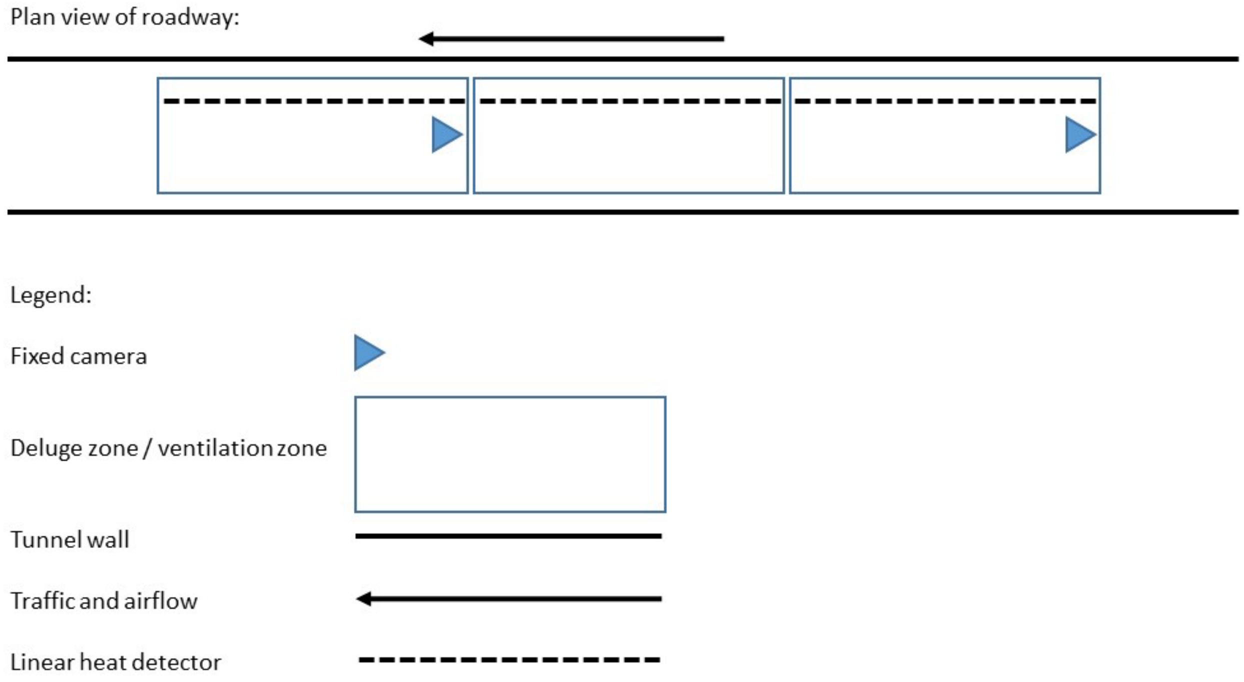
Figure 4-7: Auckland Traffic Operations Center control room [15].

4.7.2 CCTV

Activation of the FFFS at an early stage of a fire incident gives the best chance of optimal performance. Achieving this goal typically involves manual activation of the FFFS by the tunnel operator. This is because a fire is more often visible on CCTV before an automatic means (e.g. linear heat detector) activates. Once the fire location has been identified (via the camera ID and/or clearly visible markings on the tunnel walls), the operator activates the corresponding FFFS zone. It is imperative that operators can easily and accurately identify the fire locations.

Figure 4-8 and Figure 4-9 provides an example of design integration between a CCTV system and FFFS in an Australian tunnel [15]. This figure shows (fixed) camera locations at or near zone boundaries. Where fixed cameras are used at regular spacing, placing a camera within a zone, instead of at the boundaries, can confuse the operator who then needs to check multiple cameras to confirm a zone.

PTZ cameras can be used for fire location identification, however, the operator in this case will rely heavily on wall markings; careful thought needs to be placed in the design of wall markings to ensure that the operator can accurately locate the fire considering all the variables (e.g., factors such as camera direction, tunnel bore, and orientation of traffic in the camera view can influence the choice).



Source: FHWA

Figure 4-8: Example of CCTV and FFFS integration [15].

CCTV Example

- Zones on the image shown are D30 and D29

- Zone D30 is the foreground

- Zone D29 is the background

Source: FHWA

Figure 4-9: Example of CCTV and FFFS integration [15].

4.7.3 Egress Provisions

Egress points (e.g. exit doors to escape passages) are generally positioned equidistant from each other along the tunnel. Use of egress doors within active FFFS zones may be limited due to visibility reduction, noise (the active FFFS is in fact very loud [106]), physical restriction, and psychological stress. Placing egress points at consistent distance from the ends of an FFFS zone, however, can help to limit the impacts of FFFS on the egress points. A regular placement also has advantages for orientation in the tunnel with respect to FFFS zones, egress zones and ventilation zones.

Egress points are also used by fire fighters to enter the tunnel. If fire fighters enter the tunnel in the middle of an active FFFS zone, they could experience significant disorientation, slowing their subsequent response [107]. Standpipe placement, where possible, can also be coordinated with egress points so that fire fighter access is consistent.

4.7.4 Ventilation

The air velocities due to the ventilation can cause FFFS water delivery region to shift away from the active zones. CFD results in Figure 4-10 show the extent of water delivery drift for a longitudinal ventilation system with a large droplet FFFS. In this example, activation of the zone where the fire is located and one zone upstream mitigates drift effects, and assures that water reaches the target. For a small droplet (water mist) system, the drift may be more substantial than shown here; models can help to determine this drift. Note that jet fans near the FFFS zone should be activated only if necessary. In the region near a jet fan's outlet there will be high velocity relative to the average velocity of the tunnel, which will exacerbate the water delivery drift.

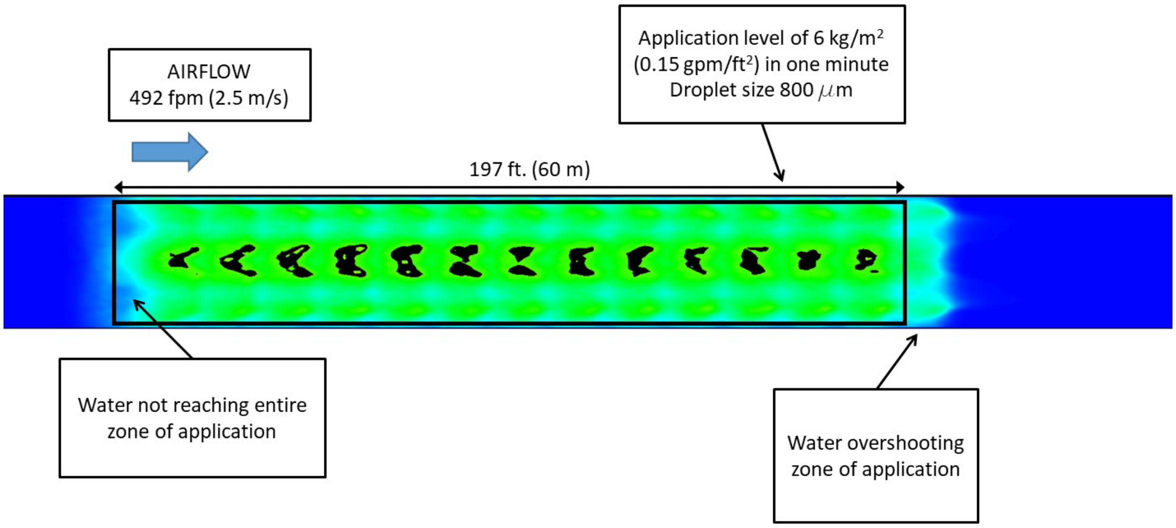


Figure 4-10: Example of FFFS and tunnel ventilation integration-CFD results.

4.7.5 Traffic and Operations

After a fire is identified, traffic must no longer be allowed to enter the tunnel. In unidirectional traffic, the vehicles downstream of the fire are expected to exit the tunnel while those upstream are expected to stop (a common assumption in tunnel fire-life design). The system must be designed such that the FFFS are never activated over live traffic (unless traffic has been told to stop and motorists ignore instructions). Active FFFS reduces motorist visibility (shown in Figure 4-11) and potentially vehicle traction. These increase the chance of a vehicle collision and exacerbates the emergency and create an unsafe situation.

Source: FHWA

Figure 4-11: Effect of FFFS on visibility [15].

4.8 Maintenance Requirements

Maintenance requirements for FFFS are outlined in NFPA 25 [8], Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems. This standard defines the frequency and specific requirements of inspection and maintenance routines. These must be followed to ensure the system is in a state of readiness and will perform as expected in an emergency. Requirements range from visual inspection to component testing and the frequency depends on the specific device, ranging from daily checks of functionality for items such as a heating system, to quarterly or longer durations for tests of specific components. Table 4-6 establishes task requirements and frequency for each specific component typically used for the FFFS. Additional maintenance and inspection measures are needed for systems with pumps, and any additional electrical equipment. Requirements for fire alarms, initiating devices, electronically activated solenoid valves, and all other electronic components are defined in NFPA 72 [104]. Many jurisdictions have additional requirements for individuals who install, test, and maintain these systems, including document retention requirements.

The importance of proper FFFS maintenance, system testing and operator training cannot be overemphasized. NFPA 25 was developed in response to numerous system failures in major fire events that were the direct result of improper maintenance, testing and/or training. Note these testing requirements may be more stringent than the current version of the TOMIE manual [13].

Table 4-6: Typical NFPA 25 maintenance requirements for fire protection systems [8].

System component (general summary only, check standard NFPA 25 for details)	**Requirement**	**Frequency**
Deluge valves – general	Maintenance	Annually
Deluge valves – enclosure	Visual inspection	Weekly
Deluge valves – exterior	Visual inspection	Monthly
Deluge valves – gauges	Visual inspection	Weekly
Deluge valves – priming water	Test	Quarterly
Deluge valves – low air pressure alarm	Test	Annually
Deluge valves – full flow	Test	Annually
Control valves – general	Maintenance	Annually
Control valves – sealed	Visual inspection	Weekly
Control valves – locked	Visual inspection	Monthly
Control valves – tamper switches	Visual inspection	Monthly
Control valves – position	Test	Annually
Control valves – operation	Test	Annually
Control valves – supervisory	Test	Semiannually
Alarm valves – exterior	Visual inspection	Monthly
Alarm valves – interior, strainers, filters, orifices	Visual inspection	5 years
Check valves – interior	Visual inspection	5 years
5 years	Test	Annually
Hose connections	Test	5 years
Hose racks	Test	5 years
Fire department connections	Visual inspection	Quarterly
Backflow preventer and assembly	Test	Annually
Backflow preventer – double check assembly (DCA) valves	Visual inspection	Weekly
Backflow preventer – double check detector assembly (DCDA)	Visual inspection	Monthly
Backflow preventer – valves secured with locks or electrically supervised in accordance with applicable NFPA standards	Visual inspection	Weekly
Reduced pressure assemblies (RPA)	Visual inspection	Weekly
Reduced pressure detector assemblies (RPDA)	Visual inspection	Weekly
All drains	Test	Quarterly
Main drain	Test	Any time used
Water flow alarm	Test	Quarterly
Hydraulic nameplate	Visual inspection	Quarterly
Hangers/seismic bracing	Visual inspection	Annually
Pipe and fittings	Visual inspection	Annually
Sprinklers	Visual inspection	Annually
Spare sprinklers	Visual inspection	Annually

4.9 Sprinkler Effectiveness

The implementation of FFFS in a road tunnel can provide effective control of even large fires and provide benefits in improved efficiency of other related life-safety systems. The decision whether to take full advantage of these benefits can depend on level of confidence that the FFFS will perform as intended in a fire event. Sprinkler systems have consistently proven to be reliable elements in overall fire protection strategies since their first use over one hundred years ago. The effectiveness of these systems continues to improve as sprinkler system design and component development evolves to address prior causes of system failures.

The two primary components of system effectiveness are operational reliability and efficacy. Operational reliability represents the probability that a sprinkler system will activate in a fire event. Efficacy represents the probability that the sprinkler system will affect the development of the fire. Sprinkler effectiveness studies rely on fire incident data and report on a combination of operational reliability and efficacy to obtain an overall effectiveness value. System ineffectiveness and system failures decrease the overall effectiveness value.

The two types of failure discussed in the studies are fail-safe and fail-dangerous. The fail-safe condition occurs when the sprinkler system activates in the absence of fire. The fail-dangerous condition occurs when the sprinkler system does not activate in the presence of fire. Most fire incident data do not differentiate between the two failure conditions. Reported statistics represent overall effectiveness with a combination of failure cases [108] [7]. For road tunnel FFFS designers need to take into consideration effectiveness statistics relevant to conditions and expected levels of care, maintenance and supervision to be provided for the system. In general, road tunnels are considered critical infrastructure elements and will be provisioned with highly developed FLS systems. Any estimation of predicted system effectiveness should take this into consideration.

The results of ten U.S. sprinkler system effectiveness studies were summarized to report average overall effectiveness and categorized system failures [7]. These include fail-safe incidents. The studies compiled fire incident data from thousands of building fires with data collected as recently as 2014. The most common causes for sprinkler system failure were: inappropriate system shut-off, manual intervention including accidentally closed valves, failure to trip a manual release, and flawed sprinkler system design. The primary reasons for fail-safe condition were rupture of pipes due to freezing and mechanical damage to system components. Overall, the components used in these systems were found to be highly reliable and rarely contributed to system failure or ineffectiveness [9]. Primary reasons for the fail-dangerous conditions included: lack of maintenance, fire of insufficient size to activate the system, and sprinkler system not located at the fire origin.

Most of the failure types noted can be mitigated by appropriate system design, by proper maintenance in accordance with related standards, through system monitoring, and by regular training. Road tunnel FPLS systems are typically monitored 24 hours and operated by highly trained personnel. Design follows related industry standards and is generally highly scrutinized. Considering the components of system reliability reported in the study [9], for systems that are properly designed, maintained, monitored, and operated, the effective system reliability is calculated to be greater than 99.4% [9]. This value is based on thousands of fire events where sprinklers were activated, across five years of data collection. It should be noted that these statistics were summarized for traditional sprinkler systems as described in NFPA 13. Other types of systems, such as high-pressure mist and fixed film forming foam systems, are significantly more complex. Reliability values would be expected to be lower.

By understanding the causes of sprinkler system failures, a series of best practices can be implemented to improve overall effectiveness. NFPA 13 and NFPA 25 provide requirements to assure the proper installation and supervision of sprinkler systems for optimal effectiveness. Most system failures have occurred due to operational and maintenance issues. Systems must be monitoring for water flow, valve position, and available pressure in accordance with the NFPA 13 and NFPA 72 standards. Personnel working with the sprinkler system must understand procedures during a fire event and know how to make the appropriate decisions in response to conditions. Sprinkler systems, including individual components and equipment, must be maintained and tested at regular intervals as required by equipment manufacturers and NFPA 25. NFPA 13 provides detailed requirements for the proper design of sprinkler systems.

4.10 Summary

Questions raised in the introduction are outlined below, along with comments on the findings of the literature survey and synthesis.

How do water application rate and other design parameters link to NFPA 502 goals?

As per Table 4-4, the water application rates (with deluge systems) of 0.30 gpm/ft^2 to 0.15 gpm/ft^2 (12 mm/min to 6 mm/min) could achieve fire control. No water application achieved fire suppression unless the fire was sufficiently exposed such that water application could directly reach the seat of the fire. Recent data suggest water application rates as low as 0.05 gpm/ft^2 (2.2 mm/min) could achieve control. Further study with testing or analysis (CFD) is needed to better quantify threshold limits and system details (nozzle layout, type, water application rate) with respect to NFPA 502 goals.

What level of effort is needed for maintenance and inspection of FFFS?

Regular maintenance and inspection of FFFS are critical to their effective operation. On average, FFFS have a high effectiveness value [7]. Maintenance requirements for FFFS are outlined in NFPA 25 [8]. Many valve components need weekly or monthly inspections; however, the sprinkler piping and nozzles only need annual inspections. Based on data from thousands of fire events, the reliability rate of a properly designed, maintained, and operated FFFS is 99.4% [9].

5 FIXED FIRE FIGHTING SYSTEM - EMERGENCY VENTILATION SYSTEM INTERACTION

The goal of this section is to identify the main considerations towards developing an integrated FFFS and EVS design.

5.1 Tunnel Emergency Ventilation Schemes

The purpose of the tunnel EVS is to control the smoke and heat from a fire, so that motorists are protected and, if necessary, can evacuate safely. It also supports safe accessibility for fire fighters and other emergency responders [12]. Several types of EVS are used in road tunnels, including natural ventilation, longitudinal ventilation, semi-transverse ventilation with single point extraction, and full transverse ventilation.

Natural ventilation: Air movement is driven by the environmental conditions outside the tunnel, conditions inside the tunnel and piston effect of travelling vehicles; refer to Figure 5-1. The environment outside the tunnel causes flow through the tunnel by elevation, pressure and temperature differences, as well as prevailing external winds.

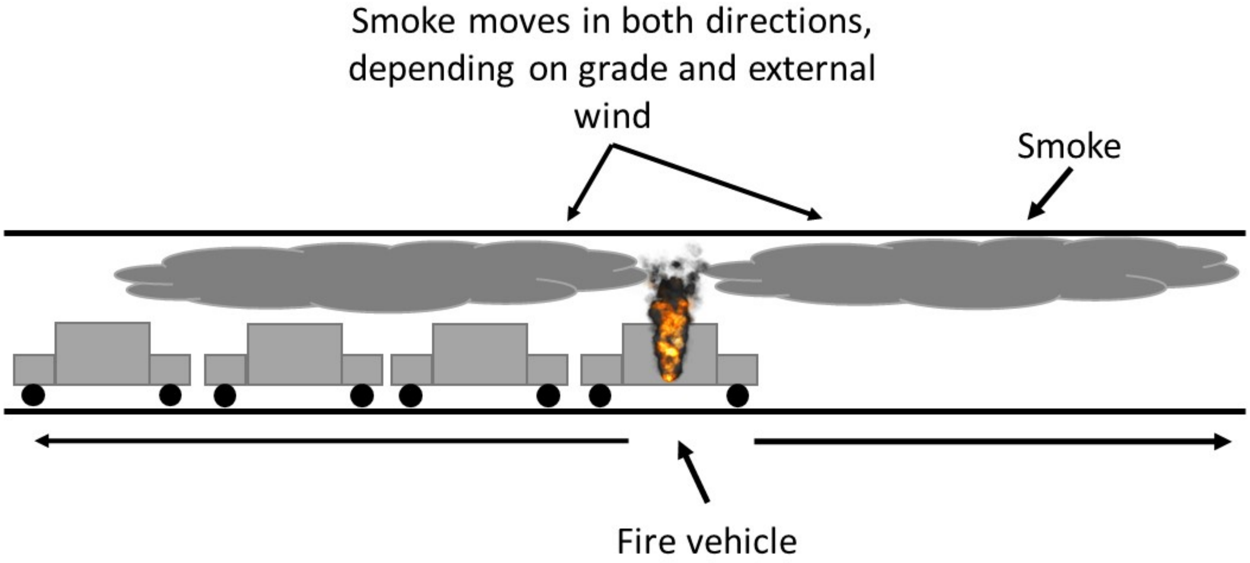


Figure 5-1: Natural ventilation scheme.

Longitudinal ventilation: Fans are used to generate air flow through the tunnel. Air is blown through the tunnel bore, therefore having one portal act as an inlet and the other an outlet; refer to Figure 5-2. Ventilation is typically achieved by jet fans installed in the tunnel ceiling space.

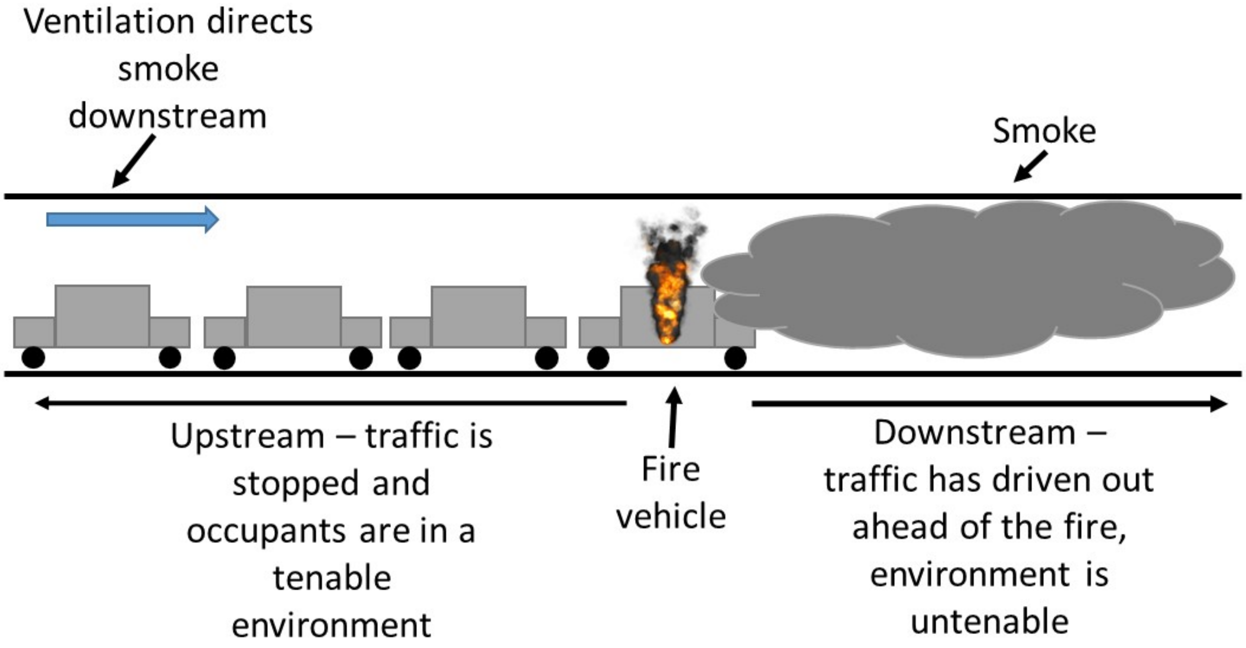


Figure 5-2: Longitudinal ventilation.

Semi transverse ventilation: Fans are used to move air within a duct that can be configured to evenly exhaust or supply air throughout the tunnel; refer to Figure 5-3.

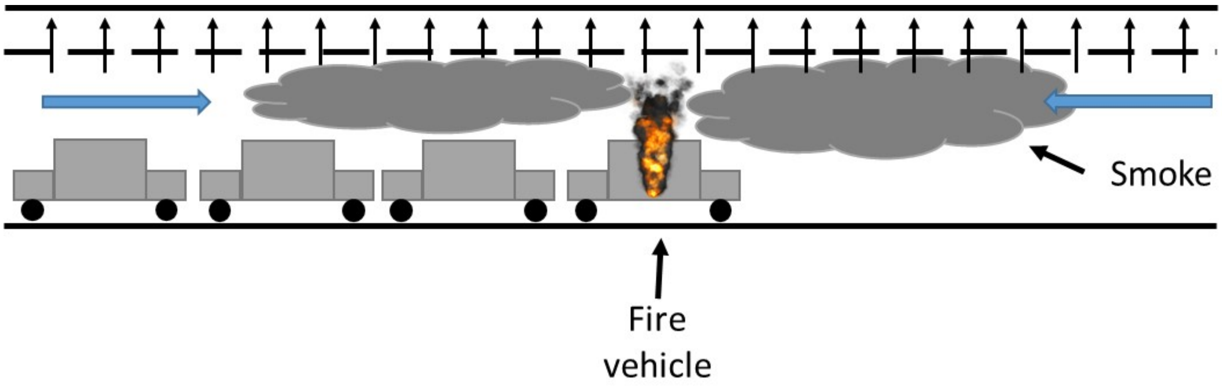


Figure 5-3: Semi transverse ventilation.

Full transverse ventilation: Fans are used to move air within ducts configured to evenly exhaust and supply air throughout the tunnel; refer to Figure 5-4. Air is typically exhausted at the tunnel ceiling and supplied at the roadway.

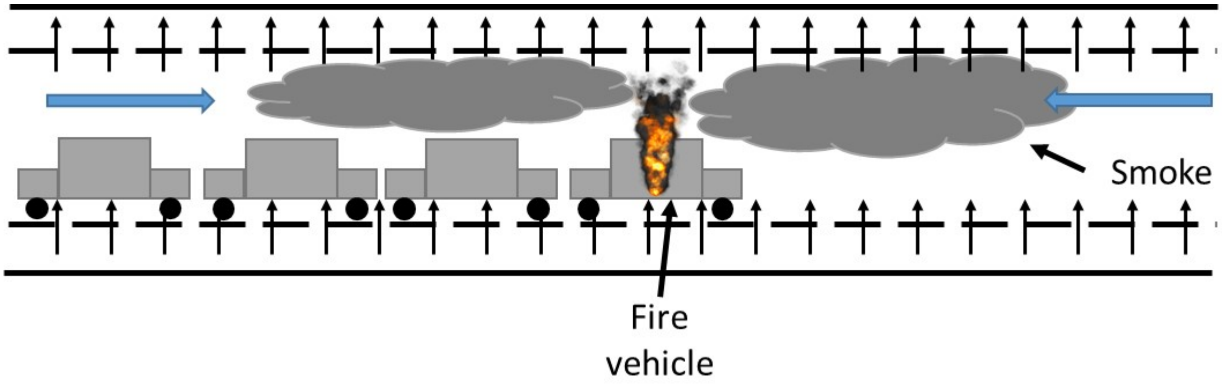


Figure 5-4: Full transverse ventilation.

Single point extraction: An exhaust duct is used to remove smoke. The location for smoke removal is based on opening one or more dampers, at a location corresponding to the location of the fire. The goal is to limit smoke spread and sometimes more than one damper needs to be opened to achieve the desired degree of smoke control. Figure 5-5 provides a schematic.

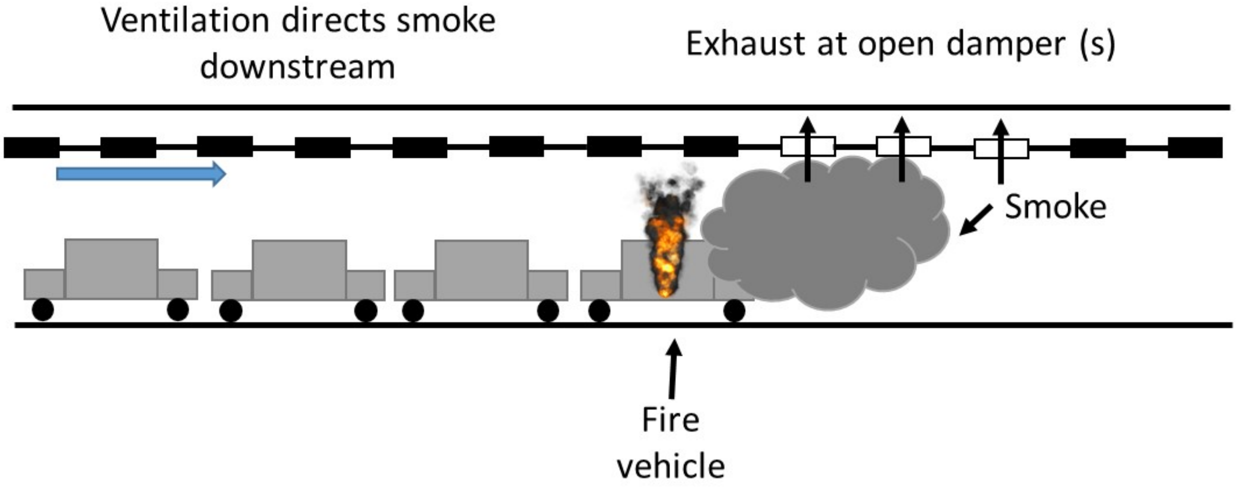


Figure 5-5: Semi-transverse single point extraction.

Most of the older (pre-1990) U.S. highway tunnels are ventilated via with transverse ventilation system [109]. During the 1990s the Memorial Tunnel program [28] established that a longitudinal ventilation system is effective at managing smoke from a fire, and the trend for most US tunnels constructed since then is to employ longitudinal ventilation (refer to Table 2-9). The Memorial Tunnel tests showed that air velocities of 500 fpm to 580 fpm (2.54 m/s to 2.95 m/s) were sufficient to manage backlayering of smoke (refer to Section 5.2 for a definition) for FHRRs ranging from 10 MW to 100 MW [28] [29].

This section focuses initially on longitudinal ventilation and interaction with the FFFS. The principles discussed for longitudinal ventilation will also have applicability for other types of ventilation systems and discussion is provided following the treatment for a longitudinal system. The intent of this review is to focus on the interaction between EVS and FFFS, and not to give an in-depth account of all aspects of the EVS. Both NFPA 502 and AASHTO have published guidelines and provide a detailed discussion about the approach to designing emergency ventilation for U.S. highway tunnels [12] [29]. Ventilation practices have also been produced by PIARC [110], which cover operational approaches for emergency ventilation.

The principal factors to focus on in developing an integrated FFFS-EVS design are established in NFPA 502. The following are relevant NFPA 502 requirements [12]:

> 11.2.2 In all cases, the desired goal shall be to provide an evacuation path for motorists who are exiting from the tunnel and to facilitate fire-fighting operations.
>
> 11.3 Design Objectives. The design objectives of the emergency ventilation system shall be to control, to extract, or to control and extract smoke and heated gases as follows:
>
> > (1) A stream of noncontaminated air is provided to motorists in path(s) of egress in accordance with the anticipated emergency response plan (see Annex C).
> >
> > (2) Longitudinal airflow rates are produced to prevent backlayering of smoke in a path of egress away from a fire (see Annex D).
>
> 7.6.2(3) Means shall be provided downstream of the incident site to expedite the flow of vehicles from the tunnel. Where it is not possible to provide such means, under all traffic conditions, the tunnel shall be protected by FFFS or other suitable means to establish a tenable environment to permit safe evacuation and emergency services access.

Section 7.6.2(3) of NFPA 502 is of interest because it acknowledges FFFS as a potential solution to providing safe egress and firefighter access. The NFPA 502 requirements above for ventilation and traffic management can be met by providing one of, or a combination of, the following [19]:

- 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 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 FFFS and longitudinal ventilation, such that during an incident vehicles downstream are in tenable conditions due to the impact of the FFFS on the fire.

5.2 Critical Velocity for Smoke Control

Critical velocity is a key design parameter for a longitudinal EVS. The methods used for predicting critical velocity in tunnels typically include semi-empirical equations [111] [112] and, in recent years, CFD modeling [113]. Critical velocity is a function of input parameters including FHRR, tunnel geometry and tunnel slope.

Per NFPA 502 the following definitions are used herein for backlayering and critical velocity [12]:

- **Backlayering** – Movement of smoke and hot gasses counter to the direction of ventilation airflow.
- **Critical velocity** – The minimum steady-state velocity of the ventilation airflow moving toward the fire, within a tunnel or passageway that is necessary to prevent backlayering at the fire site.

Several studies have been conducted to develop equations for critical velocity and some of the earliest documentation dates back to the 1960s [112]. In recent times, several small-scale and full-scale tests, as well as CFD models, have been conducted and used to derive equations for the critical velocity. Critical velocity equations arising from studies by Kennedy [113], Wu and Bakar [111], and Li and Ingason [112] are considered herein. Behavior of the equations is demonstrated by way of application to the Memorial Tunnel cross section; refer to Figure 5-6. Characteristic dimensions of the Memorial Tunnel include: width = 28.7 ft., height = 26 ft., fire pan height = 3 ft., area = 640 ft^2 and perimeter = 97 ft. [28].

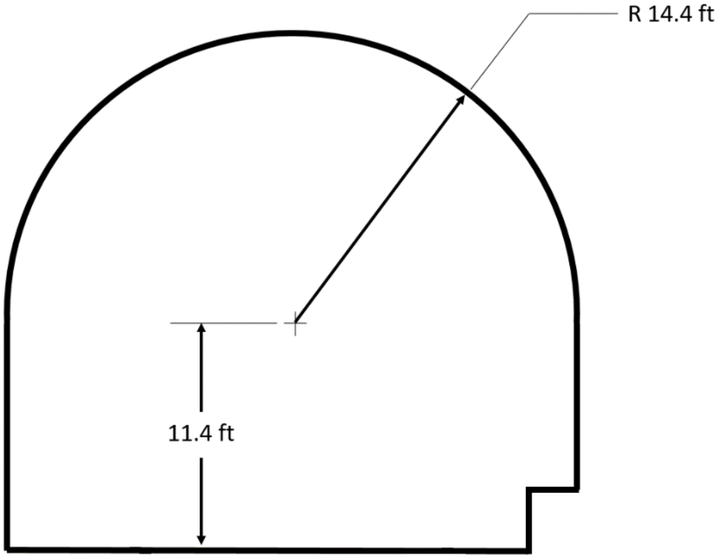


Figure 5-6: Memorial Tunnel cross section for longitudinal ventilation tests [28].

5.2.1 Critical Velocity Equations

There are generally two forms of critical velocity equations applied in practice:

- NFPA 502 equations, based on Froude number modeling, 2014 edition [114] and the 2017 edition of NFPA 502 [12].
- Equations based on small-scale tests and dimensional analysis, including equations by Wu and Bakar [111], Lee and Ryou [115], and Li and Ingason [112].

5.2.1.1 NFPA 502 Editions Prior to 2017

Sometimes known in the industry as the “Kennedy” equation, this equation was used in NFPA 502 up until the release of the 2017 edition. The equation is based on Froude number (ratio of gravity forces to pressure forces) modeling, appropriate to a situation where the flow is fully turbulent and viscous forces are negligible [113]. In deriving the equation conservation of energy and mass principles are applied equations, as well as the ideal gas equation to relate density and temperature [113].

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f} \right)^{\frac{1}{3}}$$

$$T_f = \left(\frac{Q}{\rho C_p A V_c} \right) + T$$

$$K_g = 1 + 0.0374 \, (G)^{0.8}$$

Figure 5-7: Equation. Critical velocity, NFPA 502 2014 edition [114].

In Figure 5-7 symbols are as follows: A is the area perpendicular to the flow (m^2), C_p is the specific heat of air (kJ/kg/K), g is the acceleration due to gravity (m/s^2), G is the absolute value of tunnel grade as a percent, H is the height of duct or tunnel measured from base of fire of the fire site (m), K_1 is 0.606, which is the Froude number factor raised to the negative one third power, K_g is the grade factor which is 1 for 0% or uphill and per the provided equation for downhill grade, ρ is the average density of the approach (upstream) air (kg/m^3), Q is the heat the fire adds directly to air at the fire site (kW), T is the temperature of the approach air (K), T_f is the average temperature of the fire site gases (K), and V_c is the critical velocity (m/s).

Some points on application of Figure 5-7 include the following:

- The critical velocity equation above is two equations, one for temperature at the fire site, and one for critical velocity. The equations are solved via an iterative process.
- The variable for height (H) is the length of the buoyant force. This means rather than being the tunnel height, it is the distance between the base of the fire and the tunnel ceiling.
- The area (A) is the annular area, tunnel area less area of blockages (such as vehicles).
- The equation is valid for a typical “two-lane” highway tunnel (a typical lane is 11.5 ft. or 3.5 m wide). For very wide road tunnels the equations should be solved for velocity (not flow rate) as though the tunnel were two lanes wide [113].
- The equation assumes that the fire must be sufficiently wide and high such that no air can move past the fire without cooling it (the fire plume and incoming airflow are well mixed). This assumption is reflected by having a constant Froude number [116].

Figure 5-7 takes the effect of tunnel slope (gradient) on critical velocity into account via the constant K_g. Gradient is the slope expressed as a percent, and the correction factor should be used in scenarios where smoke is to be directed downgrade. For level and uphill grades, K_g is 1.0.

The critical velocity formulation from Figure 5-7 was validated as part of the Memorial Tunnel Fire Ventilation Test Program (MTFVTP) [28]. The experiment results and comparison to the NFPA 502 equation are plotted in Figure 5-8. Backlayering in these tests was judged visually by monitoring from a CCTV located 200 feet upstream of the fire, and by a sudden temperature rise at thermocouples placed (approximately) 100 feet upstream of the fire. When backlayering was prevented, it was noted to be generally contained to less than 40 feet upstream of the fire [28]. Therefore, the velocity noted here might not be, strictly speaking, critical velocity to prevent backlayering, but instead might represent confinement velocity (magnitude sufficient to stop smoke movement upstream of the fire but not to prevent backlayering).

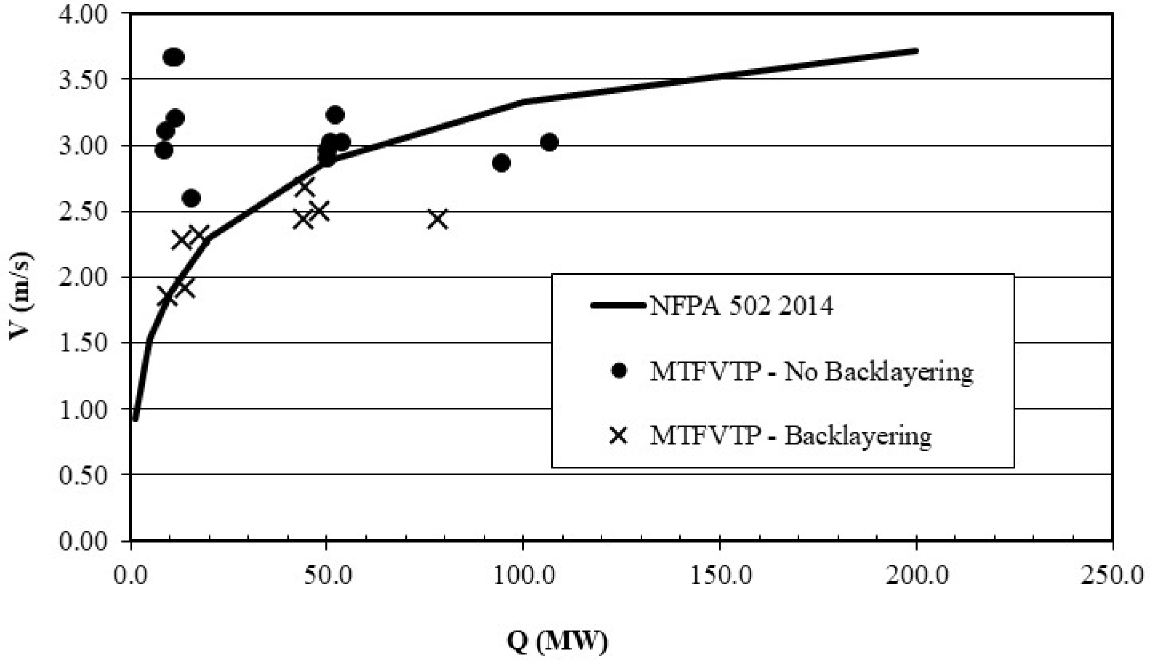


Figure 5-8: Graph. Critical velocity results from the Memorial Tunnel Fire Tests (MTFVTP) [28] for the NFPA 502 equation prior to 2017.

5.2.1.2 NFPA 502 2017 Equation

The NFPA 502 equation was modified for the publication of NFPA 502 2017 [12]. The constant Froude number assumption was revisited, based on scale model tests, and a new formulation comprising a variable Froude number was implemented. The 2017 equation is almost identical to the 2014, except that the constant (K_1) in the equation, varies based on FHRR. The updated form is provided in Figure 5-9.

Figure 5-10 provides a plot of the critical velocity using both the 2014 and 2017 NFPA 502 equations. The equations converge to the same result for FHRRs equal or greater than 100 MW but at lesser FHRRs the 2017 equation predicts an increased critical velocity. Agreement with Memorial Tunnel test data is improved for the 2017 equation at FHRRs below 100 MW.

The Froude number for lower FHRRs in NFPA 502 2017 is increased relative to the NFPA 502 2014 equation (critical velocity is inversely proportional to Froude number). The NFPA 502 2014 equation assumed a constant Froude number of 4.5. Li and Ingason provide an in-depth discussion of this point and demonstrate that the constant Froude number approach was based on a single FHRR value [116]. When data are examined for a range of FHRRs they demonstrate, by comparison with small-scale test data, that smaller Froude numbers are appropriate for lower FHRRs.

The Froude number approach assumes full and instantaneous mixing between the incoming air and fire plume, which Li and Ingason point out is not a valid assumption when the tunnel is very wide [116] and that the critical velocity can be severely underestimated in this case. A similar point was made in other references [113]. It is concluded by Li and Ingason [116] that because the Froude number is affected by tunnel geometry and FHRR, that critical velocity equations based on a Froude number approach are unsuitable for development of a general critical velocity equation that takes all parameters into account.

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f} \right)^{\frac{1}{3}}$$

$$T_f = \left(\frac{Q}{\rho C_p A V_c} \right) + T$$

$$K_g = 1 + 0.0374\,(G)^{0.8}$$

Figure 5-9: Equation. Critical velocity, NFPA 502 2017 edition [12].

In Figure 5-9 symbols are as follows: A is the area perpendicular to the flow (m^2), C_p is the specific heat of air (kJ/kg/K), g is the acceleration due to gravity (m/s^2), G is the absolute value of tunnel grade as a percent, H is the height of duct or tunnel measured from base of fire at the fire site (m), K_1 is 0.606, which is the Froude number factor raised to the negative one third power, K_g is the grade factor which is 1 for 0% or uphill and per the provided equation for downhill grade, ρ is the average density of the approach (upstream) air (kg/m^3), Q is the heat the fire adds directly to air at the fire site (kW), T is the temperature of the approach air (K), T_f is the average temperature of the fire site gases (K), and V_c is the critical velocity (m/s). If Q is greater than 100 MW, K_1 is 0.606, for Q of 90 MW, K_1 is 0.620; 70 MW is 0.640; 50 MW is 0.680; 30 MW is 0.740; and for Q less than 10 MW, K_1 is 0.870.

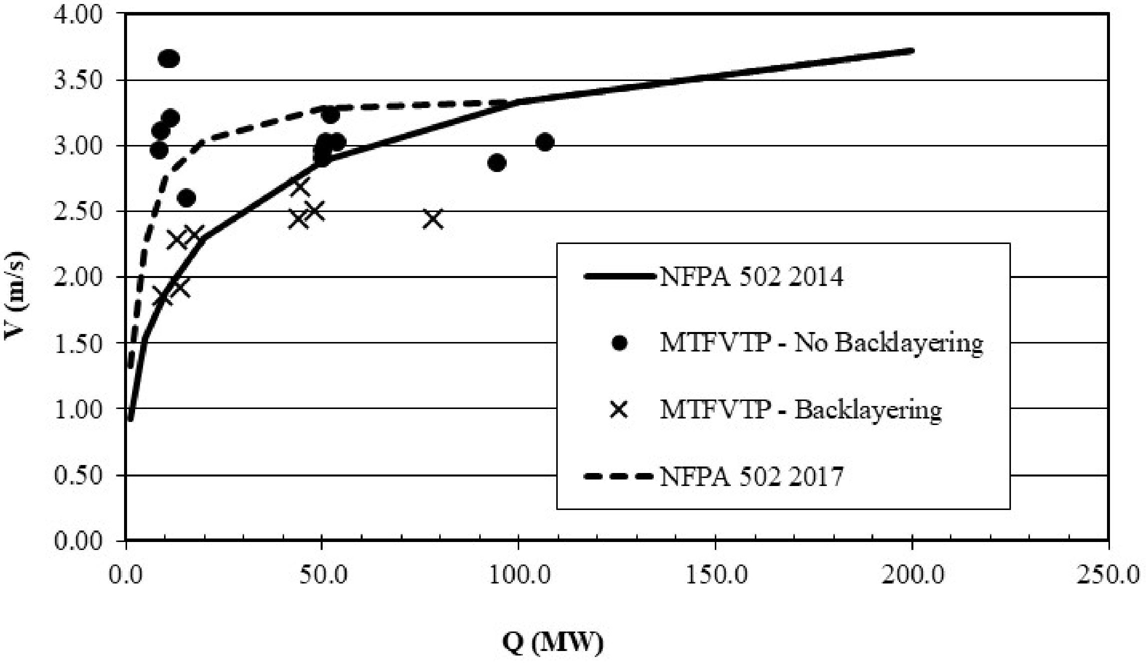


Figure 5-10: Graph. Critical velocity results from the Memorial Tunnel Fire Tests (MTFVTP) [28] for the NFPA 502 2017 equation.

5.2.1.3 Equations Based on Small-Scale Models and Dimensional Analysis

Small-scale models are used by researchers to conduct testing of fires in tunnels at reduced geometry and FHRR. This enables research to be conducted at a laboratory scale, which is less expensive than full-scale testing in a tunnel because the test geometry is smaller and the FHRR is reduced, thus creating less smoke and heat to manage. The principal of scaling is based on matching the Froude number (ratio of inertia forces to gravitational forces) between laboratory and full-scale scenarios [115]. Figure 5-11 provides the scaling equations.

Wu and Bakar [111] used scale models and CFD models to investigate critical velocity in a tunnel for a range of cross sectional shapes. The scale models used a propane burner with a FHRR ranging from 1.4-28 kW (equivalent to 2.5-50 MW in full-scale). Five different cross sections were tested with varying aspect ratios. The test geometry was an approximate 1/10 scale. The investigation was motivated by some uncertainties in the equations based on models founded on Froude number preservation; primarily the lack of scalability for the FHRR and tunnel geometry. Data from the tests were analyzed and it was found that the data scaled very well based on a dimensionless velocity and FHRR. A new formulation for the critical velocity was developed, as per Figure 5-12. Tunnel slope was later incorporated into this equation based on additional test data [117].

$$
\begin{aligned}
Fr &= \left(\frac{V_M^2}{g l_M}\right) = \left(\frac{V_F^2}{g l_F}\right) \\
V_M &= V_F \sqrt{\frac{l_M}{l_F}} \\
\dot{V}_M &= \dot{V}_F \left(\frac{l_M}{l_F}\right)^{5/2} \\
Q_M &= Q_F \left(\frac{l_M}{l_F}\right)^{5/2}
\end{aligned}
$$

Figure 5-11: Equation. Froude number scaling relationships [115].

In Figure 5-12 symbols are as follows: Fr is the Froude number, g is the acceleration due to gravity (m/s^2), l is length (m), Q is the heat release rate (kW), V is the ventilation velocity (m/s), and $\dot{V}$ is the volumetric flow rate in (m^3/s). The subscript F is for the full-scale facility parameter; the subscript M is for the model parameter.

$$
\begin{aligned}
Q'' &= \left(\frac{Q}{\rho_o C_p T_o \sqrt{g D^5}}\right) \\
V'' &= \begin{cases} 0.40[0.20]^{-1/3}[Q'']^{1/3} & Q'' \leq 0.20 \\ 0.40 & Q'' > 0.20 \end{cases} \\
V &= V'' \sqrt{gD} \\
V(\theta) &= V[1 + 0.008\theta]
\end{aligned}
$$

Figure 5-12: Equation. Critical velocity, Wu and Bakar [111].

In Figure 5-12 symbols are as follows: C_p is the specific heat of air (kJ/kg/K), g is the acceleration due to gravity (m/s^2), D is the hydraulic diameter of the tunnel (m), ρ_o is the average density of the approach (upstream) air (kg/m^3), Q is the convective fire heat release rate (kW), Q'' is the dimensionless heat release based on the hydraulic tunnel diameter, T_o is the ambient temperature (K), V is the critical velocity (m/s), V'' is the dimensionless critical velocity, and θ is the absolute value of the tunnel slope expressed as a percent, which applies when the slope is downhill.

The critical velocity for the Memorial Tunnel configuration, computed using the equations of Wu and Bakar (Figure 5-12), is plotted in Figure 5-13, along with the test data from the Memorial Tunnel program. At low FHRRs (less than 50 MW) the critical velocity generally lies in between the NFPA 502 2014 and 2017 equations. The agreement with Memorial Tunnel test data is very good.

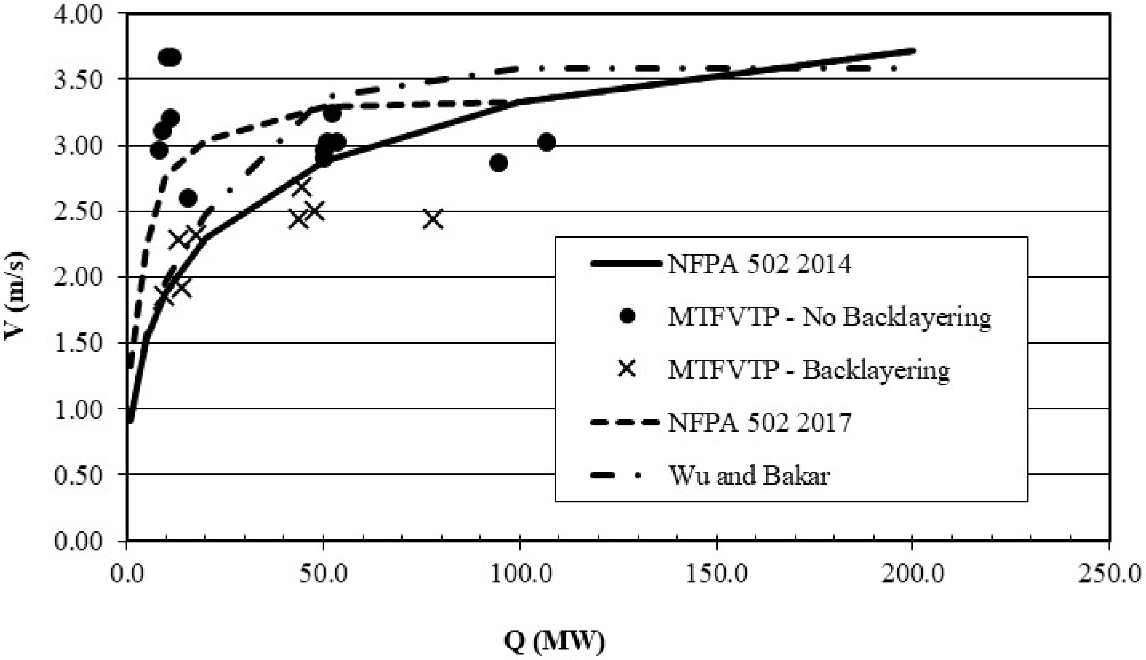


Figure 5-13: Graph. Critical velocity results from the Memorial Tunnel Fire Tests, based on equation by Wu and Bakar [111].

Li et. al. [112] conducted tests in two small-scale tunnels; one was a square cross section (0.25 m by 0.25 m) and the other was an arched section approximately 0.38 m diameter. The equations arrived at by Li and Ingason for critical velocity are similar to those of Wu and Bakar, except that Li and Ingason use tunnel height as the characteristic length (not hydraulic diameter) and the overall velocity predicted is slightly larger than that predicted by Wu and Bakar.

Li and Ingason also looked at the impact of cross section and tunnel slope on the critical velocity [118]. CFD simulations were conducted using the Fire Dynamics Simulator software. Small-scale and full-scale tunnels were simulated and excellent agreement with test data (at small-scale) was achieved. After this, the critical velocity expressions were modified to factor in the impact of tunnel aspect ratio. Li and Ingason also looked at the effect of fire source height and found it to be insignificant for their critical velocity equations [118].

One final modification to the critical velocity equation was made to factor in the tunnel slope by Li et. al. [119]. The modified equations were based on numerical simulations and the form is like earlier forms except for the inclusion of slope. Figure 5-14 provides the final formulation developed. Note that in these equations aspect ratio is computed based on the tunnel height divided by tunnel width. When the tunnel is of a circular or arched profile, the height used is based on the distance from the base of the tunnel to the crown (i.e. the maximum height). In addition to the equation for critical velocity, an equation was provided for backlayering length; refer to Figure 5-15.

Figure 5-16 shows results using the modified equation. The equation by Li et. al. was derived using similar principles to Wu and Bakar but a larger value of the critical velocity is predicted. This was attributed (speculatively) to the fact that Wu and Bakar utilized a water spray system in their testing to keep the tunnel walls cool at the location of the test fire; this may have caused some excessive heat removal and a reduction of the critical velocity. The equation predicts a critical velocity that is conservative with respect to Memorial Tunnel test data.

$$V^*_{cr} = \begin{cases} 0.81(1+0.008s)\phi^{-1/12}Q^{*1/3} & Q^* \leq 0.15\phi^{1/4} \\ 0.43(1+0.008s) & Q^* > 0.15\phi^{1/4} \end{cases}$$

Figure 5-14: Equation. Critical velocity equation, Li et al. [119].

In Figure 5-14 symbols are as follows: Q^* is the dimensionless heat release rate, s is the absolute value of the tunnel slope expressed as a percent, which applies when the slope is downhill, V^*_{cr} is the dimensionless critical velocity, and Φ is the aspect ratio, which is tunnel width divided by tunnel height. The dimensionless critical velocity and heat release rate are the same as in Figure 5-12 but tunnel hydraulic diameter is replaced with tunnel height.

$$L^*_b = 18.5\,\ln\left(\frac{V_{cr}}{V}\right)$$
$$L_b = L^*_b H$$

Figure 5-15: Equation. Backlayering length equation, Li et al. [119].

In Figure 5-15 symbols are as follows: H is the height of the tunnel (m), L_b is the backlayering length (m), L^*_b is the dimensionless backlayering length, V_{cr} is the critical velocity (m/s), and V is the air velocity in the tunnel (m/s).

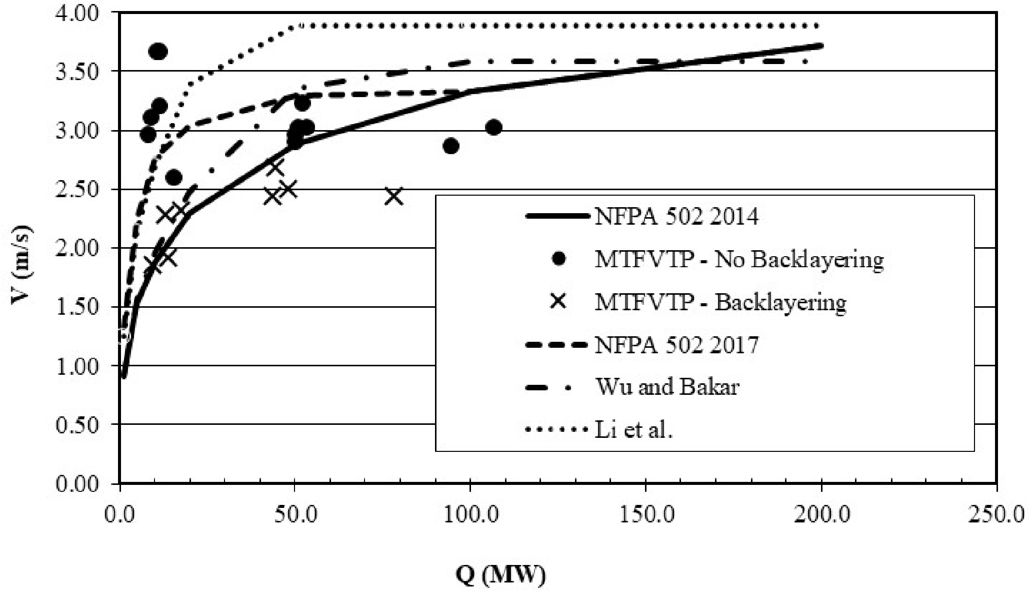


Figure 5-16: Graph. Critical velocity results from the Memorial Tunnel Fire Tests, based on equation by Li et al. [119].

The equation of Wu and Bakar was later extended by others to incorporate different tunnel aspect ratios. Lee and Ryou conducted small-scale tests for a series of five configurations, with the aspect ratio (tunnel height / tunnel width) ranging from 0.5 to 2.0 [115]. An updated scaling relationship is provided in Figure 5-17. The authors found that aspect ratio affects fire dynamics, with the smoke front velocity increasing with aspect ratio due to the increased tunnel height. The equation of Wu and Bakar was altered to include aspect ratio. The work did not consider very large fires, but instead fires up to a dimensionless FHRR of 0.2. Figure 5-18 shows results using the modified equation factoring in aspect ratio. The figure shows that the equation has limited practical applicability since it can only be used for low FHRRs.

$$
\begin{aligned}
Q' &= \left(\frac{Q}{\rho_o C_P T_0 \sqrt{A_S g D^5}}\right) \\
V &= V' A_S^{0.2} \sqrt{gD} \\
Q' &= \left(\frac{V'}{0.73}\right)^3 \\
Q' &\leq 0.2
\end{aligned}
$$

Figure 5-17: Equation. Critical velocity equation per Lee and Ryou [115].

In Figure 5-17 symbols are defined as follows: A_S is the aspect ratio, which is tunnel width divided by tunnel height, C_p is the specific heat of air (kJ/kg/K), g is the acceleration due to gravity (m/s^2), D is the hydraulic diameter of the tunnel (m), Q is the total fire heat release rate (kW), Q' is the dimensionless heat release rate, V is the ventilation velocity (m/s), V' is the dimensionless critical velocity, T_o is the ambient temperature (K), and ρ_o is the average density of the approach (upstream) air (kg/m^3).

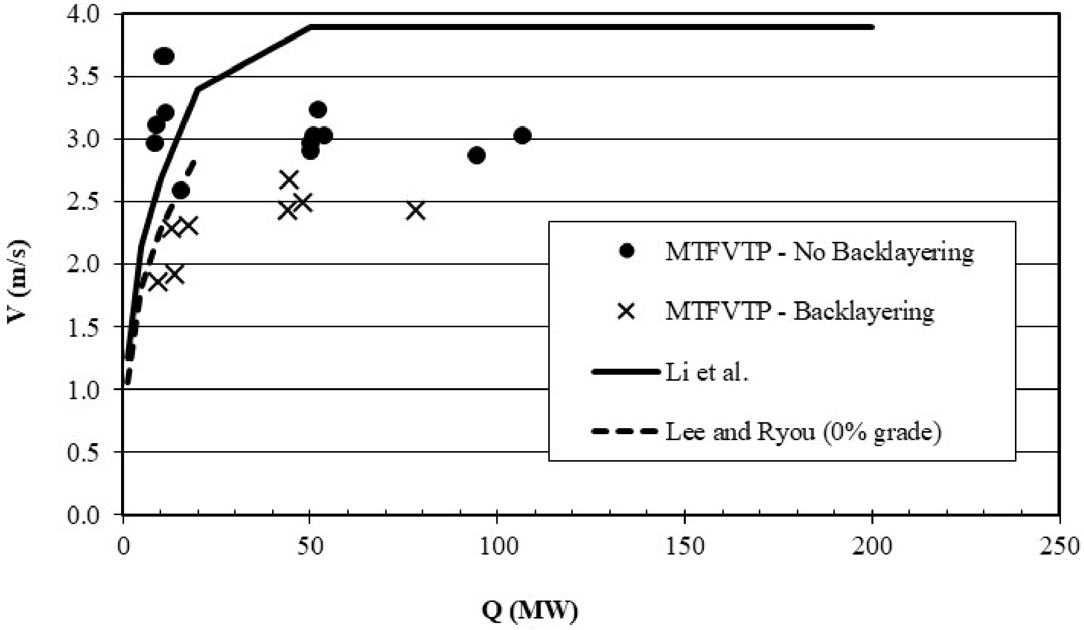


Figure 5-18: Graph. Critical velocity results from the Memorial Tunnel Fire Tests, critical velocity equation per Lee and Ryou [115]

5.2.2 Tunnel Geometry Influences

Tunnel blockage, due to vehicles or other obstructions, acts to cause a local increase in the velocity near to the fire. This results in a reduction in the critical velocity relative to the unobstructed tunnel situation. In the paper by Li and Ingason [112] a blockage occupying 20% of the tunnel cross section was placed upstream of the fire in some tests. The net effect was a reduction in the dimensionless critical velocity by around 23%.

Similarly, when the Memorial Tunnel test results were processed, it was found that velocity was increased local to the fire due to instrumentation blocking approximately 20% of the tunnel cross section. The resultant velocities were factored (increased) to account for this and found to achieve better agreement with the theoretical critical velocity [28]. A similar phenomenon of local velocity increase has been observed in CFD models [120].

NFPA 502 equations note that the cross-sectional tunnel area should be the annual area. It is not clear whether the dimensional analysis equations allow for a change in tunnel cross section.

Another geometrical factor to consider is tunnel curvature. The equations for critical velocity do not account for curvature, but this is an affect that should be considered in design as it may affect smoke behavior [121]. CFD modeling has been used to understand the impact of curvature on critical velocity and backlayering. It was shown that the critical velocity is increased by approximately 16% near to the convex wall, and that the critical velocity increases slightly with a decrease in tunnel radius [122].

Caution also needs to be exercised with respect to tunnels where there is a roadway merge or diverge. At these locations, the tunnel cross section will be wider than the mainline tunnel as it must accommodate the extra lane during the roadway geometry change section. The increased width of tunnel can result in a greater ventilation demand as the airflow needed to achieve critical velocity increases (i.e. if the velocity remains the same but the cross section is larger, airflow needed will increase). The extra ventilation demand may not be practical to meet, and CFD modeling is sometimes used to justify the smoke control strategy with an air speed less than critical velocity.

5.2.3 CFD Modeling

CFD modeling is routinely applied to tunnel fire simulation to investigate critical velocity. CFD models are particularly useful when there is a non-standard aspect to the problem, such as a very large cross section, curvature, blockages, uphill grades or an FFFS. An overview of CFD models is provided here.

Wu and Bakar [111] ran CFD simulations using a time-averaged approach with the standard k-epsilon turbulence model, with combustion included. Good agreement was achieved between CFD and experiment for the velocity profile. Agreement was not as good for temperature and it was concluded that this was due to CFD being unable to predict intermittent flame regions. Critical velocity with CFD was slightly lower than experiment.

Drake et al. [120] investigated critical velocity in a tunnel with a rail vehicle obstructing the tunnel using a time-averaged approach. The model had an average cell size of 0.24 m with finer cells near to the fire. The FHRR considered was around 15 MW and a volumetric heat source was used. The authors found that the critical velocity could be predicted with CFD. Convergence problems were encountered when the velocity was near to the critical value. This was attributed to the unsteady nature of a hot smoke layer not being captured by the steady-state model. A transient approach was used with much better convergence achieved.

Bettelini [123] used CFD modeling (time-averaged approach) to test longitudinal smoke control in a series of models with varying geometry features including ribs and blockages. One interesting point made is that the critical velocity can vary depending on whether one aims for backlayering control or backlayering prevention. A key test case in this paper is a ribbed ceiling to determine if there was any impact on the critical velocity. The ribs were at the ceiling and were varied in depth relative to tunnel height. The effect of ribs on the critical velocity was found to be minor in this case.

Fire Dynamics Simulator (FDS) was used to simulate a 100 MW fire for the Memorial Tunnel geometry with good comparison to the test data [124]. Modeling sensitivity was investigated including factors such as grid resolution (0.3 m, 0.48 m, 0.6 m cells, 0.48 m gave the best agreement with tests), inlet boundary conditions (minor impact), turbulence closure constant for the LES model (no major impact on conclusions) and the impact of baroclinic torque. The authors showed that the baroclinic torque had a major impact on results; baroclinic torque is sometimes neglected in FDS models but in tunnel situations it should be included because buoyancy and pressure effects are similar and without including baroclinic torque an excessive backlayering is predicted. The authors found some unwanted/unexpected backlayering in their results and they speculated that this could be due to poor treatment of the wall boundary conditions. The wall boundary conditions have improved greatly in FDS since this paper was published [125].

FDS models have been employed more recently on a current version of the software to study the impact of tunnel grade and cross section [119]. Good agreement with empirical correlations was achieved.

Although CFD is routinely used, it is noted that CFD models need to be applied carefully. The first reason for this is that CFD is not a panacea for all aspects of FFFS-EVS design. As demonstrated by the diagram in Figure 5-22, CFD is not needed for every element of an FFFS-EVS integration design problem. In many cases, it is better to use a complex approach such as CFD only to answer a very specific problem, and revert to simpler models where practical. This will speed up the design process, allow more sensitivity cases to be tested, and thus reduce the chances of an oversight or error. The second reason for caution with CFD, is that it is a model and therefore an idealization of a real-world phenomenon; the model must be validated for the purpose it is used for and the user must be knowledgeable and fully understand the limits of application [26].

5.2.4 Influence of an FFFS

The impact of an FFFS on critical velocity is an area of active research. Intermediate-scale fire tests were conducted by Ko and Hadjisophocleous [126] to investigate the impact of an FFFS on critical velocity. The fire in these tests, a propane burner, was shielded to prevent direct fire suppression and an FHRR ranging up to 40 MW was tested. Numerical simulations with FDS were also conducted. Water flow rates from the FFFS ranged from 0.07 gpm/ft^2 to 0.25 gpm/ft^2 (3 mm/min up to 10 mm/min). The analysis showed that the velocity necessary to control smoke backlayering was reduced when the FFFS was activated.

Equations for critical velocity were derived by Ko and Hadjisophocleous [126] using a formation like that of Wu and Bakar (dimensionless heat release rate and velocity) but with the FFFS influence included, with the equation valid up to 40 MW. Figure 5-19 provides the equation developed and Figure 5-20 provides an analysis showing the predicted critical velocity for the Memorial Tunnel test case. There is a definite reduction in the critical velocity observed, and that reduction is more pronounced when the FHRR and water application rate is increased.

Ko and Hadjisophocleous [126] defined the critical velocity in their work based on a Richardson number, which describes the ratio of buoyancy of the hot flow to the momentum of the longitudinal flow. The Richardson number equation was reduced to being a function of temperature rise measured upstream of the fire. Critical velocity was said to be achieved (backlayering prevented) if temperature rise upstream is less than 10% of the ambient temperature. Casting the equation in terms of a temperature allowed the authors to directly test the influence of cooling due to FFFS. It is noted that this criterion might not be capturing prevention of backlayering (hence, critical velocity) but should at least be determining confinement velocity. This point could be important, and a source of a possible discrepancy, when comparing with CFD models and where a model was run to prevent backlayering.

The impact of FFFS on the critical velocity for smoke control has been studied previously using CFD. A reduction in the critical velocity was observed due to the cooling effect of the water for a 100 MW FHRR; from 3.35 m/s with no FFFS, to 2.75 m/s with a FFFS operating at 0.20 gpm/ft^2 (8 mm/min) [127]. This analysis had no reduction in the FHRR modelled due to FFFS application. A reduction in the thrust needed from jet fans (for a longitudinally ventilated tunnel) was also determined based on the lower gas temperatures downstream. A similar CFD analysis found that critical velocity could be decreased approximately 0.25-0.5 m/s when FFFS were applied [14].

Some other recent studies looking at the interaction of the FFFS and EVS include the following:

- A proof of concept for use of water sprays to control smoke was investigated [128]. The ventilation boundary conditions were not very realistic as a large exhaust rate was used for a short length of tunnel. This means that the concept would have to be revisited with realistic boundary conditions to truly test the merit.
- Small-scale tests were conducted and shown to reduce critical velocity but the study stopped short of deriving a specific equation [129].

Also noteworthy here is the very large reduction of critical velocity seen with the equation of Ko and Hadjisophocleous [126]. At 40 MW FHRR and 0.30 gpm/ft^2 (12 mm/min) water application rate, the critical velocity is reduced from around 590 fpm (3 m/s) to less than 197 fpm (1 m/s), while at 0.15 gpm/ft^2 (6 mm/min) the reduction is not as dramatic (critical velocity is around 443 fpm, 2.25 m/s). The dramatic reduction at larger water application rate warrants investigation, as does the need to test the degree of reduction at higher FHRRs. If indeed large water application rates drive down the critical velocity as much as suggested here (to less than 1 m/s), that would have an enormous impact on ventilation design. Further work is needed to better quantify the situation and derive a reliable equation for critical velocity based on application of an FFFS.

$$Q'' = \left(\frac{Q}{\rho_o T_o C_p g^{1/2} D^{5/2}}\right)$$

$$V'' = \begin{cases} 0.40[0.20]^{-1/3}[Q'']^{1/3} & Q'' \leq 0.20 \\ 0.40 & Q'' > 0.20 \end{cases}$$

$$V = V''\sqrt{gD}$$

$$V_{FFFS}^2 \geq 9\frac{\sqrt{Q''}V^2}{\omega}$$

Figure 5-19: Equation. Critical velocity equation with FFFS impact factored in [126].

In Figure 5-19 symbols are defined as follows: C_p is the specific heat of air (kJ/kg/K), g is the acceleration due to gravity (m/s^2), D is the hydraulic diameter of the tunnel (m), ρ_o is the average density of the approach (upstream) air (kg/m^3), Q is the convective fire heat release rate (kW), Q'' is the dimensionless heat release based on the hydraulic tunnel height, T_o is the ambient temperature (K), V is the critical velocity without FFFS (m/s), V'' is the dimensionless critical velocity without FFFS, V_{FFFS} is the critical velocity accounting for FFFS (m/s), and ω is the water spray density (mm/min). The equation is valid up to a FHRR of 40 MW.

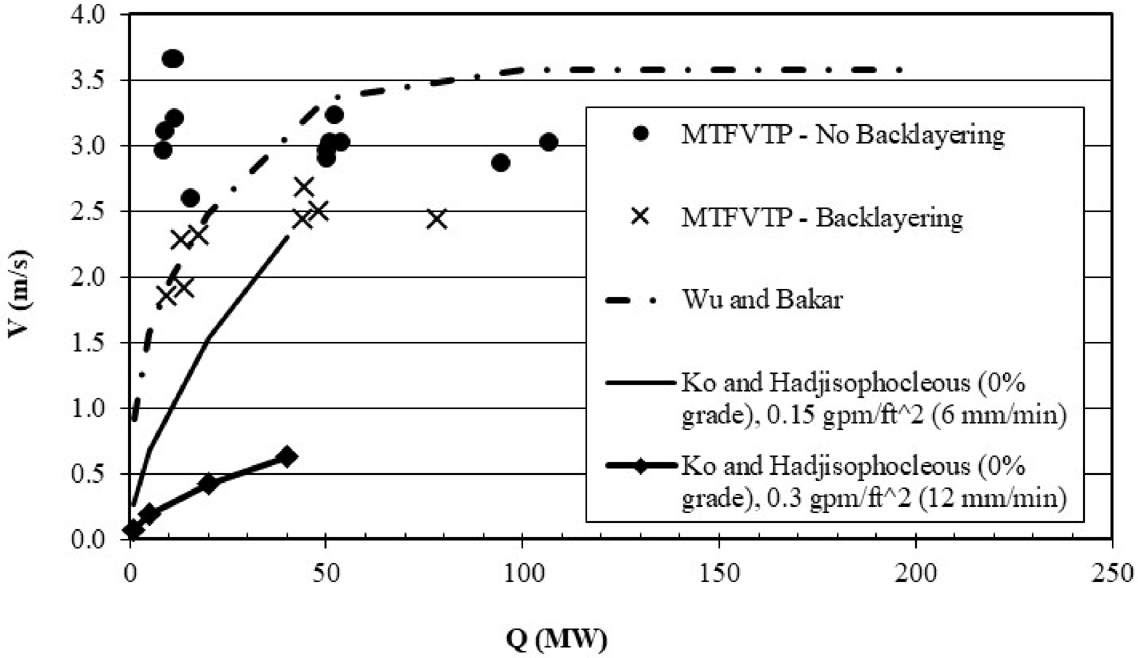


Figure 5-20: Graph. Critical velocity results from Memorial tunnel case with FFFS systems.

5.3 FFFS Impact on Tunnel Ventilation Systems

To integrate the FFFS and EVS design it is necessary to consider the approach to design of the EVS and what impact the FFFS has on various design inputs and assumptions. The discussion initially focuses on a longitudinal EVS with later sections covering transverse and natural EVS. Longitudinal ventilation is assumed to be achieved via a jet fan system or Saccardo nozzle.

To determine jet fan parameters, including thrust and number of fans, a one-dimensional steady state approach is used. The approach is based on methods outlined by the World Road Association (PIARC) [130]. A pressure (momentum) balance is iterated on to find the inlet velocity that satisfies the equation. Pressure losses due to vehicles, buoyancy, friction, external wind, and fire are equated to the pressure generated by the jet fans. Figure 5-21 provides the basic equation.

Heat transfer effects due to the fire, cooling at the wall and cooling due to the FFFS need to be accounted for as these effects influence the air temperature, which in turn impacts on the jet fan thrust, buoyancy force and air density. Additional design inputs include the ambient pressure related to the elevation above sea level. Figure 5-22 shows a schematic of the overall design process and the interrelated nature of the design inputs and analysis.

$$N_f \cdot \Delta P_j = \Delta P_{veh} + \Delta P_f + \Delta P_m + \Delta P_b + \Delta P_{fire} + \Delta P_{FFFS}$$

Figure 5-21: Equation. Pressure balance for a longitudinal EVS.

In Figure 5-21 symbols are defined as follows: N_f is the number of jet fans, ΔP_j is the pressure rise due to a jet fan, ΔP_{VEH} is the pressure loss due to vehicles, ΔP_f is the pressure loss due to wall friction, lights, FFFS pipework, entry losses, exit losses, ΔP_m is the pressure loss due to meteorological effects, including wind, ΔP_b is the pressure loss or rise due to buoyancy, ΔP_{fire} is the pressure loss due to the fire, and ΔP_{FFFS} is the pressure loss due to the FFFS spray.

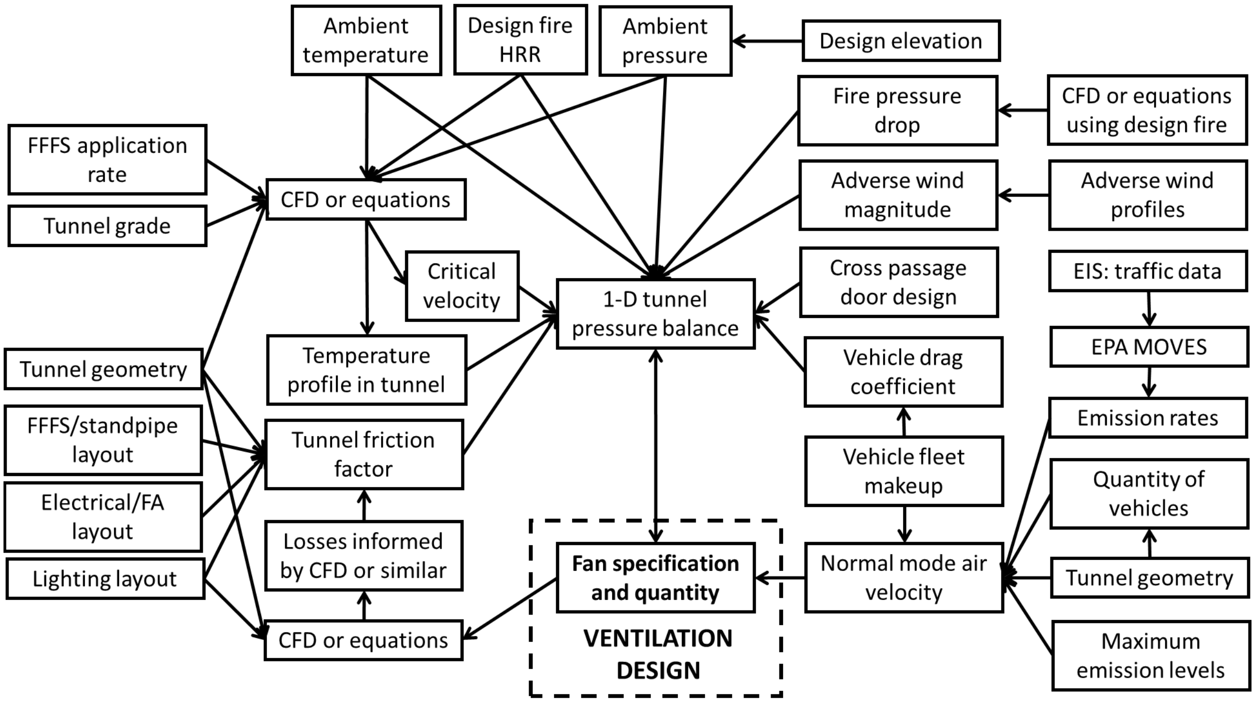


Figure 5-22: EVS design inputs and analysis.

In a tunnel environment, FFFS impacts to consider include the following:

- Fire heat release rate
- Critical velocity for smoke control
- FFFS cooling of the combustion products
- Pressure loss (airflow resistance) due to fire
- Pressure loss (airflow resistance) due to the FFFS (droplets and humidity)
- Friction losses introduced by FFFS pipework
- Water droplet deflection due to the EVS
- Tenability for egress and fire fighting

5.3.1 Fire Heat Release Rate

It is a well-established point, from full-scale tests and incident experience, that an FFFS can suppress a fire and reduce the FHRR. NFPA 502 Annex A [12] provides a summary of FHRRs for experiment scenarios with or without an FFFS operating and Table 5-1 provides a summary of data (typically for a single vehicle only; FHRR might be larger if more vehicles are involved). For tunnels using a water only FFFS, the reduction of the FHRR for EVS design is typically accepted in the industry, except for fire scenarios involving a liquid fuel spill. For more information on liquid fuel spill fires, refer to Section 3.3.3 and Section 6.3.3.

To reduce the FHRR for a design it is necessary to rely on small-scale and full-scale test data. CFD modeling is not routinely used to predict the FHRR. Section 3.4 herein provides a detailed summary of the impacts of FFFS and the order of magnitude of the FHRR reduction possible.

Table 5-1: FHRR data [12].

Vehicles	Peak FHRR (MW)	Time to peak (min)	Peak FHRR with FFFS (MW)	Time to peak FHRR with FFFS (min)
Passenger car	5-10	0-54	Not available	Not available
Multiple passenger cars	10-20	10-55	10-15	35
Bus	25-34	7-14	20	-
Heavy goods truck	20-200	7-48	15-90	10-30
Flammable / combustible liquid tanker	200-300	Not available	10-200	Not available

5.3.2 Critical Velocity for Smoke Control

Critical velocity for fires with FFFS operating is discussed in Section 5.2.4. The equation from Ko and Hadjisophocleous [126] is valid for an FHRR up to 40 MW. Full-scale test data for critical velocity with an FHRR more than 40 MW and FFFS operating are not currently published in the literature. For an increased FHRR beyond 40 MW there is no specific equation or data and it is necessary to use CFD modeling or testing. CFD models have been used successfully to predict critical velocity (refer to Section 5.2.3).

Additional full-scale or small-scale test data (at equivalent FHRR greater than 40 MW) would be useful for validating the CFD models.

The application of water via FFFS reduces critical velocity. Specific approaches for CFD models should be developed to ensure consistent and accurate application for critical velocity prediction.

5.3.3 FFFS Cooling of Combustion Products

The ability of FFFS to cool the products of combustion is well-established [11]. Testing has shown the cooling effect of water sprays on the combustion products. An energy budget can be used to describe cooling potential of the FFFS. Figure 5-23 shows the concept.

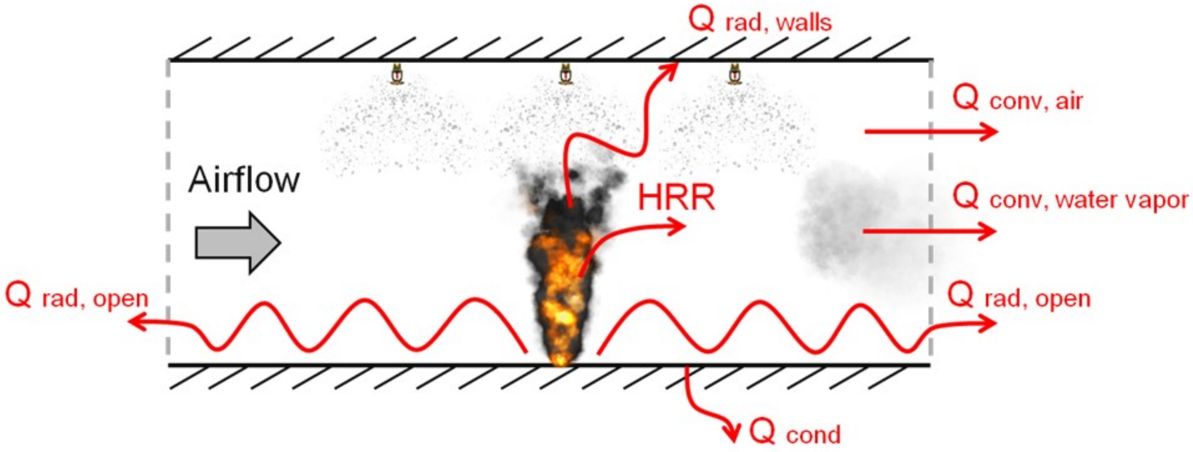


Figure 5-23: Energy budget concept

CFD models using FDS have been validated for recording the energy balance in a scale model tunnel [72]. It was found that heat lost to the walls by radiation was 52% of the overall FHRR when backlayering occurred, and it was reduced to 42% when the velocity was large enough to prevent backlayering. Considering convective heat flux to walls, it was concluded that 67% of the FHRR is transferred to the walls when velocity is less than critical, and around 50% is transferred to the walls when the velocity is greater than the critical value.

The energy budget with an FFFS operating has also been studied using CFD models with validation carried out on a scale model tunnel [131]. A longitudinal velocity was applied and the FFFS was a (small droplet) mist system. The energy budget was considered in terms of energy going to the tunnel walls (24% of the FHRR), convection out of the tunnel exit (33% of the FHRR), and absorption by water mist (approximately 50% of the FHRR). The water application rate was such that the fire was suppressed but not extinguished, thus allowing the energy budget to be studied. It was found that 47% of the water applied to the tunnel space did not contribute to cooling (i.e. the process was 53% efficient, based on the energy carried out by water mist divided by the total energy carrying potential of the water injected).

Cooling by water spray is reliably modeled with CFD. Parameters that affect the cooling potential include the droplet size, water application rate and ventilation velocity. A deeper understanding of nozzle parameters versus modeled nozzles, and sensitivity of results to inputs would be beneficial.

Accounting for the cooling effect in the design will reduce temperature downstream of the fire. Cooling can reduce the buoyancy that the ventilation system must manage (if venting smoke downhill). Cooling can reduce the peak temperatures that equipment will be exposed to; this will help to shorten recovery time after an incident and it will limit jet fan derating downstream of the fire.

5.3.4 Pressure Loss Due to Fire

The pressure loss (flow resistance) due to the fire is a complicated value to predict, and is typically estimated using either CFD data or an empirical formula. Equations are presented in the literature for the purposes of computation of a pressure loss due to fire. The first equation considered is taken from the governing equations of the SVS (Subway Ventilation Simulation) software [132]. SVS is a one-dimensional flow solver, aimed for use in rail tunnels, but is applicable to road tunnels as well. Its calculation of the fire pressure loss is based on Figure 5-24.

$$\Delta P_{fire} = \frac{\rho_0 v_{in}^2}{2}\left(\frac{2T_{fire}}{T_0} - 2\right)$$

$$T_{fire} = \frac{Q_{conv}}{C_p \dot{m}} + T_0$$

Figure 5-24: Equation. SVS pressure drop equation due to fire.

In Figure 5-24 symbols are defined as follows: ΔP_{fire} is the pressure loss due to the fire (Pa), ρ_0 is the density of air (kg/m^3), v_{in} is the magnitude of the upstream velocity (m/s), T_{fire} is the temperature at the fire (K), T_0 is the ambient temperature (K), Q_{conv} is the convective portion of the fire heat release rate (W), C_p is the specific heat of air (J/kg/K), and $\dot{m}$ is the mass flow rate of air (kg/s).

One limitation of this equation is that it does not account for the width of the tunnel. In a typical two-lane tunnel, the fire may occupy most of the cross section, and the pressure loss is averaged over the cross section. However, applying this averaged value to a six-lane tunnel may overestimate the total loss. In these wider tunnels, most single vehicle fires will not occupy the entire width of a six-lane tunnel, and therefore the loss averaged over the cross section should, in theory, be lower for the larger tunnel (unless the fire involves many vehicles and occupies the entire cross section).

A recent paper by Carlotti and Salizzoni [133] uses dimensional analysis of multiple empirical formulae and compares the results with small-scale experimental data to derive a new equation for the pressure drop, shown below in Figure 5-25. This equation is the most conservative and is recommended for use in EVS design.

There are no references that discuss the pressure loss due to fire when FFFS is activated. The pressure loss expression is based on the FHRR and mass flow rate over the fire; which implies that the pressure loss is in turn, related to the temperature of the fire region. The FFFS operation would likely reduce this pressure loss due to the reduction of the FHRR but further research is needed to quantify this.

$$\Delta P_{fire} = \frac{3 Q_{conv} v}{C_p T_0 D_h^2}$$

Figure 5-25: Equation. Pressure drop equation recommended for EVS design [133].

In Figure 5-25 symbols are defined as follows: ΔP_{fire} is the pressure loss due to the fire (Pa), Q_{conv} is the convective portion of the fire heat release rate (W), v is the magnitude of the upstream velocity (m/s), C_p is the specific heat of air (J/kg/K), T_0 is the ambient temperature (K), and D_h is the hydraulic diameter of the tunnel (m).

5.3.5 Pressure Loss Due to the FFFS

Pressure loss due to a FFFS has potential to act as a flow impediment for a longitudinal EVS due to water drop drag and acceleration. Furthermore, water expands by a factor of around 1,700 when it evaporates. Such expansion can impede ventilation.

Pressure loss due to water drops can be estimated by calculation as follows. Water droplets are assigned a typical diameter and are assumed to fill the tunnel cross section over a length corresponding to the FFFS zones activated. The drag coefficient for a sphere in a free stream is used to estimate the drag on each droplet which can then be summed over all droplets to compute the overall force (based on an assumed velocity in the tunnel). The total drag force is then divided by the tunnel area to determine the effective pressure loss. This same approach of estimating drag can also be used to compute droplet acceleration due to ventilation.

The impact of steam formation on airflow can be considered as follows:

- When water evaporates a mixture of air and water vapor is generated. To estimate the airflow impediment, it is necessary to consider the mixture from a psychrometric perspective. The key factor from psychrometric theory is that air can hold a limited amount of water vapor for a given temperature; the dew point temperature. At this temperature and water vapor concentration the air is said to be saturated and the relative humidity is 100%. At the same temperature air, will only hold more water vapor if the pressure is increased, such that the water vapor becomes superheated steam [134].
- When FFFS are active in a fire water will evaporate and there is potential that more water evaporates than air can hold at saturated conditions. This might lead to a situation with superheated steam being generated. The literature suggests that steam generate and oxygen displacement are factors in the effectiveness of water mist as a fire fighting technology [70]. This is especially the case in an application where the room is sealed off and pressure can increase. However, in a tunnel the gas can expand and thus will not remain superheated but return to saturated conditions. Any excess water would condense back to the liquid state.
- Test data show that the steam does not remain superheated in a tunnel. If the steam did remain in a superheated state, there would be very large increase in the volume of gas; to preserve the mass flow rate through the tunnel between upstream and downstream of the fire, the air speed downstream of the fire would need to increase dramatically. Furthermore, there would be a large decrease in oxygen content. Velocity data and oxygen concentration data from the LTA and Runehamar tests show almost no change in the tunnel air speed downstream after the FFFS is operated, nor is there much change in oxygen concentration. Figure 5-26 shows a snapshot of data from a full-scale test and the changes in air speed are minimal. Figure 5-27 shows the concentration downstream in a free burn test and there is a noticeable decrease in oxygen concentration, which is due to the large FHRR. Figure 5-28 shows the same result in a test with FFFS and here there is almost no oxygen concentration change downstream.

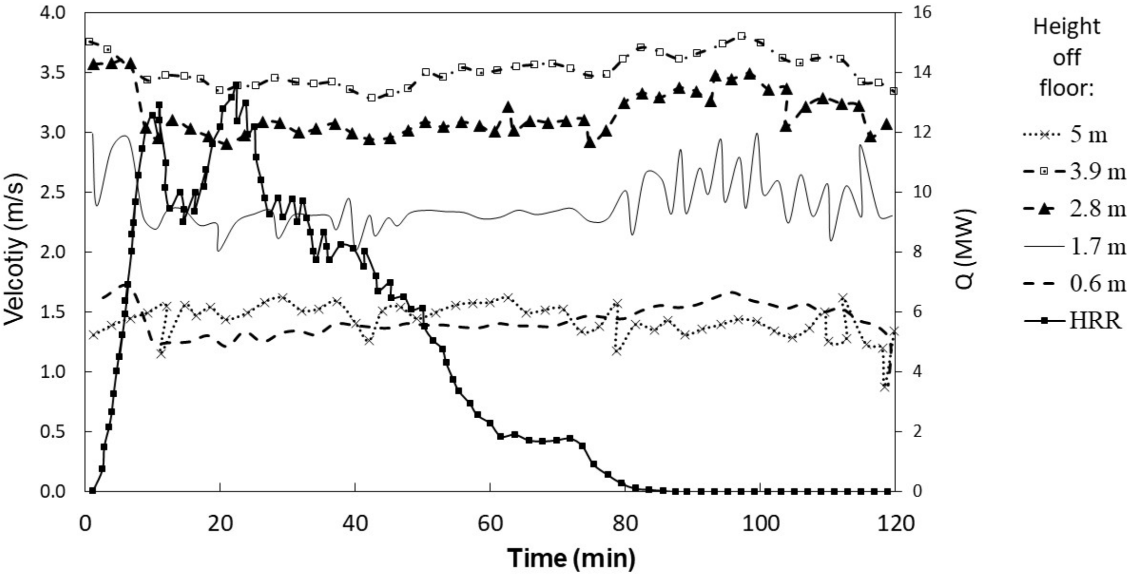


Figure 5-26: Graph. Airspeed downstream during an FFFS test [135].

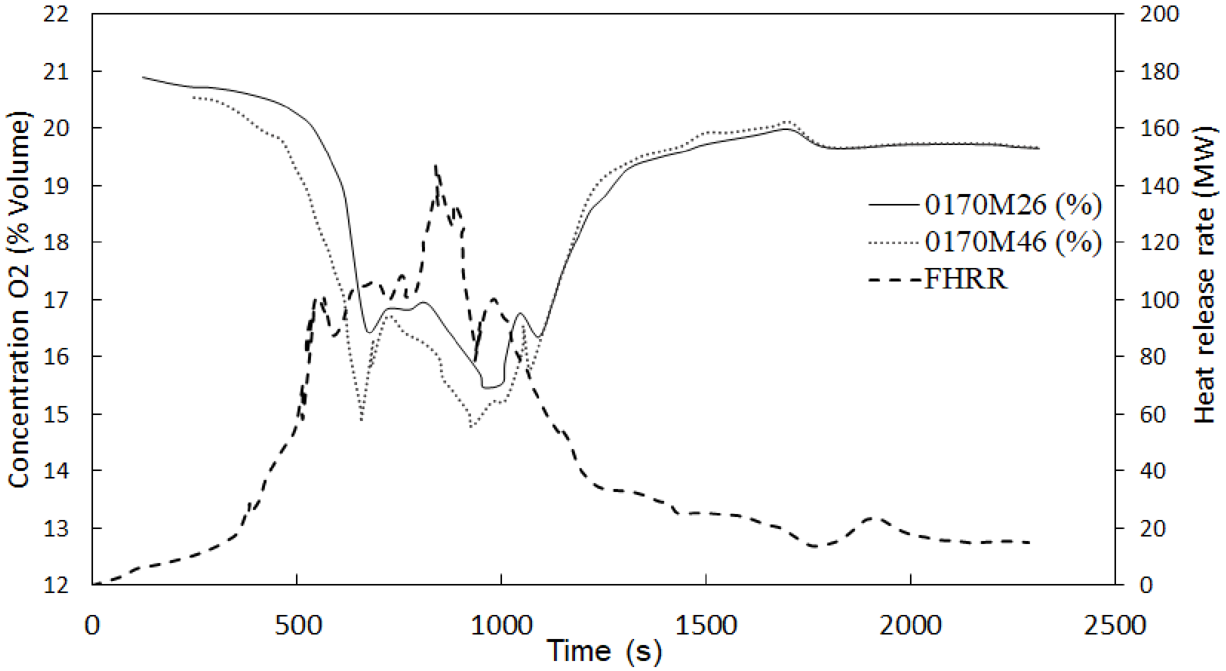


Figure 5-27: Graph. LTA test oxygen concentration downstream of the fire with no FFFS [4].

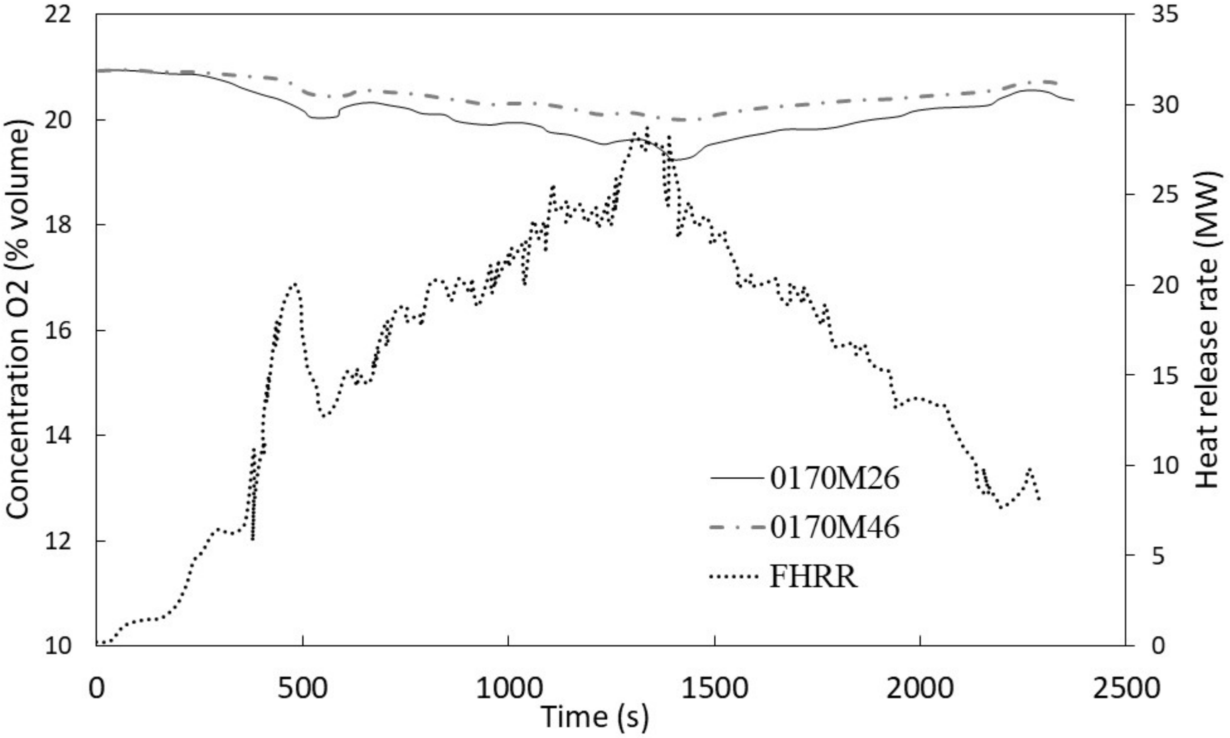


Figure 5-28: Graph. LTA test oxygen concentration downstream of the fire with FFFS operating [4].

The fact that the mixture remains saturated implies a limit on how much FFFS can cool since the process of condensation requires that the water vapor phase lose energy to convert back to a liquid. When conducting a CFD model of the FFFS this factor should be accounted for to ensure that FFFS cooling is not over predicted. CFD software such as FDS appears to track water vapor content but it may not account for the saturated vapor limit. It is possible to compute water vapor content and hence allow any changes in density to be estimated.

Research on the impact of water droplet drag and water vapor formation on pressure loss experienced by the ventilation system is minimal. A review article on the aerodynamic aspects of the FFFS concluded that the impacts should be included in a ventilation design [136]. Further work, including testing and modeling to quantify measured impacts and compare with estimates, would be useful for ventilation design.

5.3.6 Friction Losses Due to FFFS Pipework

Factors that contribute to tunnel friction factor include the construction method (and hence the surface finish) as well as services in the tunnel. Typical friction factor for a road tunnel is on the order of 0.01 to 0.025 [137].

The introduction of an FFFS will increase the tunnel friction factor due to main and branch pipework (typically 6 to 12 inches in diameter), assuming these components must be mounted in the tunnel roadway. If valves are housed in the main tunnel, then these will also increase the tunnel friction factor.

Equations and published empirical loss coefficients can be used to estimate the tunnel friction factor per Figure 5-29.

$$\frac{1}{\sqrt{f_w}} = -1.8\log\left[\left(\frac{\epsilon/D_H}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right]$$

$$f_s = \frac{D_H}{LA_t}\sum_{i=1}^{i=N} N_i C_{D,i} A_i F_i$$

Figure 5-29: Equation. Friction factor computation.

In Figure 5-29 symbols are defined as follows: f_w is the wall friction factor, ε is the surface roughness (m), D_h is the hydraulic diameter (m), Re is the Reynolds number, f_s is the friction factor due to element, for example CCTV, lighting, FFFS, L is the length of the tunnel (m), N is the number of units of each element in the length of the tunnel, C_D is the drag coefficient, A is the area normal to the velocity (m^2), F is the interference factor, and A_t is the tunnel cross section (m^2).

When objects are spaced closely together, the sum of their friction effects is decreased due to shielding (aerodynamic shadowing). Figure 5-30 provides the interference factor as referenced in Figure 5-29 [138].

$$F = 0.0035\frac{S}{W} + 0.44$$

Figure 5-30: Equation. Interference factor.

In Figure 5-30 symbols are defined as follows: Where F is the interference factor, S is the spacing of obstructions (m), and W is the width of obstructions (m).

There are no recent articles that document friction factor contribution of FFFS components. Empirical data would be helpful to validate the method outlined here.

5.3.7 Water Droplet Deflection Due to the EVS

Experiments for water droplet drift for three types of nozzles have been conducted [139]. Nozzles included spiral nozzles (K=216 and K=153) and a pendent nozzle (K=115). Wind speeds of 5 m/s, 10 m/s and 40 m/s were applied. Spray from pendent style nozzles was found to drift 4-12 times more than the spiral nozzle in a wind of 5 m/s.

Computer modeling of water spray drift showed a significant downstream drift of water in a 5 m/s wind [140]. The area of water application was found to double due to the crosswind, which amounts to a halving of the density of water application. Small droplets were also noted to be entrained and sent further downstream of the nozzle. This has been observed in full-scale tunnel applications [15]. The authors correctly note that aggregated volume of the smallest droplets is negligible relative to the total volume of water applied and when several nozzles are activated (as an array) then there is no net reduction in water application rate.

Tunnel ventilation, with air speeds in the order of 2-5 m/s, will cause the FFFS spray to drift from the desired zone of application. The effect will be exacerbated with water mist. Figure 5-31 shows an example of a CFD model result for a deluge system. Figure 5-32 shows an example result for a water mist system and the exacerbated effect of droplet drift is observed. Generally, effects of water droplet drift can be mitigated by providing an FFFS with enough capacity to activate multiple FFFS zones, compensating for droplet drift [15]. CFD modeling can be used to assess the drift and confirm the operational approach.

Where a jet fan or Saccardo nozzle ventilation system is used, there will be higher air speeds local to the fan discharge. Manufacturers can provide nozzle spray data and drift for different wind speeds [15] and for scenarios where jet discharge exceeds the test data, a CFD model could be used to determine the drift that would be experienced. The manufacturer data could also be used to firstly validate the CFD model, thus providing increased confidence in the result.

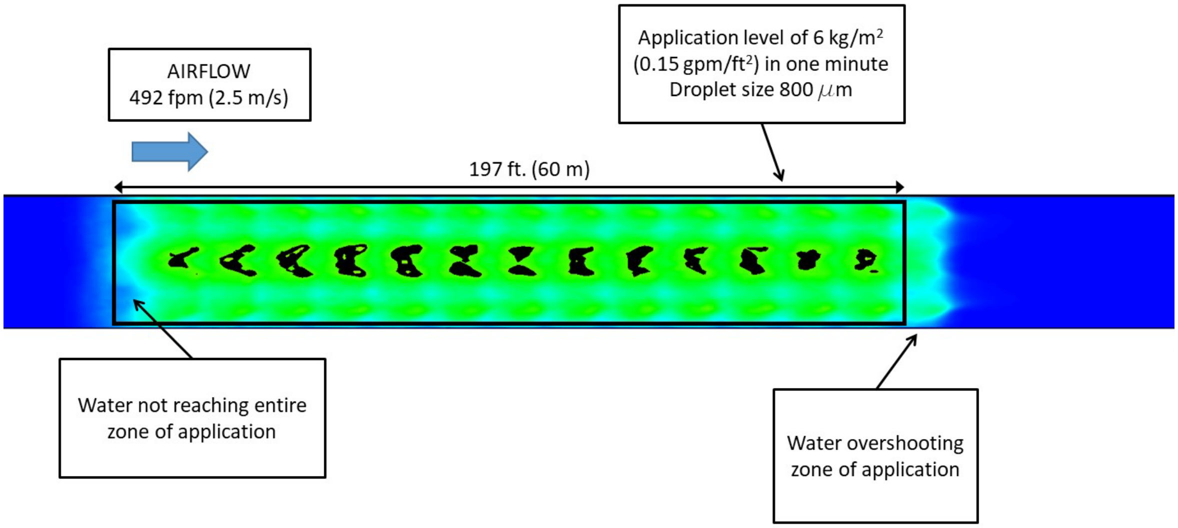


Figure 5-31: Water accumulation on a roadway with longitudinal ventilation active with a deluge system operating (average air speed approximately 2.5 m/s) (example only).

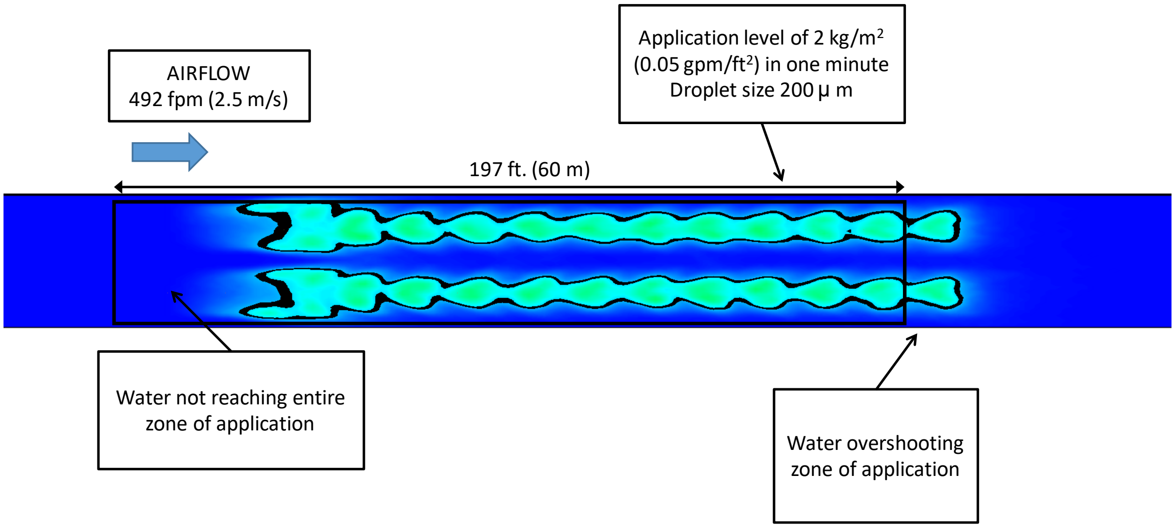


Figure 5-32: Water accumulation on a roadway with longitudinal ventilation active with a deluge system operating (average air speed approximately 2.5 m/s) (example only).

5.3.8 Tenability for Egress and Fire Fighting

Tenability for occupant egress is outlined in the annex sections of NFPA 502 [12]. Tenability is defined in the annex in terms of temperature (maximum 140 °F, 60 °C for 10 minutes), radiation heat flux (less than 2.5 kW/m^2), visibility (doors and walls visible at 10 m) and toxicity (carbon monoxide less than 450 ppm for 15 minutes). The potential impact of FFFS on each of these criteria is considered below.

The ability of FFFS to cool the surrounding environment is an established point from tests [65] and it is possible to use CFD modeling to predict the thermal environment [72].

The FFFS will cause smoke to be mixed downward in the region of application, thereby reducing visibility to almost zero [96], and possibly exposing people to increased concentrations of carbon monoxide and other gases. However, this disadvantage needs to be weighed against the advantages, especially that operation of the FFFS will likely reduce the FHRR and the production rate of smoke. Outside of the FFFS zone the smoke has been observed, under certain conditions, to rise back to the ceiling, thus restoring a smoke layer [96]. Conditions for this to occur are nuanced and would rely on certain conditions being met; note that in the test referenced the longitudinal ventilation rate was very low, there was an overhead exhaust in operation, and the smoke retained enough heat with respect to ambient temperature to rise once it had moved out of the FFFS zone.

When conducting analysis, the engineering experience is that visibility is usually lost well before the tunnel environment is completely untenable [141]. Analysis of the fractional effective dosage (FED) and fractional irritant concentration (FIC) can be used to look at the impact of fire products (toxic gases) on the evacuating people [142]. FED and FIC analysis relies on reliable data surrounding the fire products. Data on irritant gas concentration are sparse but some references are available, particularly for car fires [42] [43]. Data for heavy goods vehicles are limited.

There are two other factors for consideration with the FFFS; one is whether the FFFS dilutes the fire products and the other factor is whether the FFFS limits the combustion process such that yields of toxic gases are increased. Li and Ingason [143] investigated the interaction of ventilation with an FFFS operating in a scale tunnel. Their work showed that, after activation of the FFFS, the influence of ventilation on toxic gas product (CO) was not very significant for upstream velocities of 1.5 m/s or 3.0 m/s in the scale model (3.0 m/s and 6.0 m/s in full-scale). At an upstream velocity of 0.75 m/s (1.5 m/s in full-scale) there was an increase in the concentration of CO by a factor of 2 to 3 [143] (Figure 21). For instance, the LTA tests showed an increase in CO production by a factor of up to 5 when FFFS were suppressing the fire [4]. Li and Ingason looked at the effect of FFFS on CO production and FED [144]. CO yield increased when the FFFS was operated while the FED was unchanged or slightly reduced. The recommendation from this work was to activate FFFS early and only use systems with sufficient capability to reduce the FHRR. If velocities corresponding to critical velocity are applied (around 3.0 m/s in full-scale) it was concluded that the impact of the FFFS on CO production is likely to be negligible [143]. It is noted that, despite this conclusion, that the production toxic gases during a fire is complex, and local shielding from incoming air could result in local regions of the fire that see an increased rate of CO production.

CFD modeling can be utilized to investigate the impact of a fire on occupant egress, considering tenability requirements per NFPA 502, and extending that to a situation where FED and FIC are considered. This method has been used to demonstrate that a naturally ventilated tunnel can meet the requirements of NFPA 502 [141]. Analysis methods can be extended to consider the impact of an FFFS thereby allowing a quantitative trade-off to be made considering the benefits of an FFFS.

Tenability of motorists within an activated FFFS zone is difficult to predict. Based on operator experience, motorists tend to keep driving through an active FFFS zone, even with low visibility [15]. If motorists are trapped in the incident vehicle, the FFFS cannot be expected to extinguish the fire, especially if the fire is shielded within the vehicle [80]. It is unknown how motorists will react when evacuating from within an activated FFFS zone. In test without an FFFS, the biggest factor influencing human behavior was the tendency of evacuees to follow others [145]. Testing has shown that the evaporating of FFFS water does not produce a significant amount of steam and is not a hazard to occupants [11].

Tenability for fire fighting and rescue operations is a less complex issue than occupant egress. Firefighters would typically be wearing breathing apparatus and protective clothing. The main issue for firefighters is the thermal environment. Full-scale testing shows that firefighters can approach the fire when an FFFS is operating [65]. Fire fighting operations can be challenged by the operation of an FFFS due the large volume of water, wet fire fighting clothing and poor visibility [107]. Although visibility is not usually recognized in literature as a tenability criterion for firefighters [58], where possible, the EVS should be used to maximize visibility in order to assist fire fighting operations. Note that visibility near to the fire, typically within the fire perimeter of 100 ft. (30 m), that it is nearly impossible to control visibility due to the smoke, turbulent flow, and water spray interacting.

The impact of steam on the tenability of the environment has been a concern in the past and in the 1999 PIARC document sprinklers were not recommended due in part to the perceived risk of vaporized steam harming people [146]. Concerns about steam arose following the Ofenegg tunnel tests, however, these concerns have not proven to be of a concern in the numerous full-scale tests that have been conducted since [5] [10]. A review of water mist systems notes that one method of fire suppression by water mist systems is oxygen displacement by steam; given that water expands by a factor of 1700 in going from a liquid to a gas, there is potential for significant dilution [70]. In an enclosed room this could be significant, however, in a tunnel there are air currents and therefore this mechanism of suppression is less likely to be significant. In terms of human tenability, the concerns with steam include hot steam and oxygen dilution. Test data show that downstream of a fire when FFFS is used the minimum oxygen concentration does not drop below 19%, which is well above the minimum threshold for humans [4] (see Figure 5-28 in Section 5.3.5). In contrast, when FFFS are not applied the oxygen concentration dips to around 15% at the time when peak FHRR occurs [4]. In relation to temperatures, NFPA 502 Annex B states that saturated air at temperatures beyond 60°C can cause thermal burns to the respiratory tract; meaning that, provided temperatures are less than this threshold there should not be any risk posed by hot steam.

5.3.9 Transverse Ventilation Systems

Smoke management with a transverse ventilation system is provided by a coordinated operation of the exhaust and supply air systems. The operations are tailored to achieve a maximum longitudinal velocity and smoke extraction rate for a unidirectional tunnel. If the tunnel is bidirectional the system is operated to minimize longitudinal velocity at the fire.

A fully transverse ventilation system uses a combination of under roadway supply ducts and overhead exhaust ducts to generate airflow through the tunnel. Figure 5-33, Figure 5-34 and Figure 5-35 show the concept. Note that the black regions on the long section represent short regions of tunnel where there is no supply or exhaust duct serving the roadway, perhaps because of proximity to a portal or a transition from the duct section to the ventilation building housing the fans.

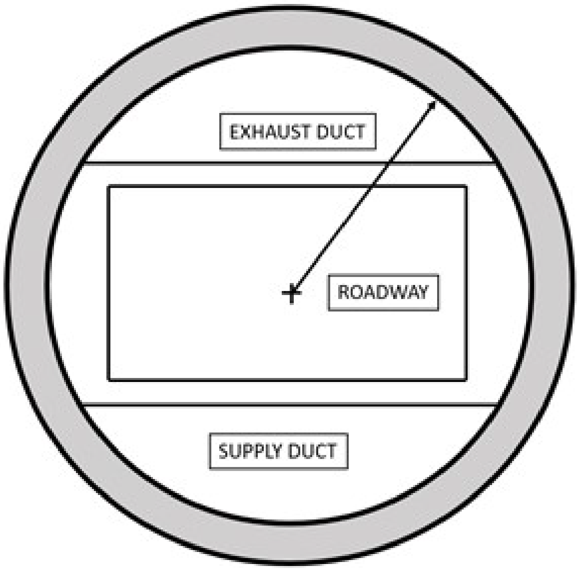


Figure 5-33: Tunnel with transverse ventilation showing ducts.

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Figure 5-34: Photo of a tunnel with transverse ventilation.

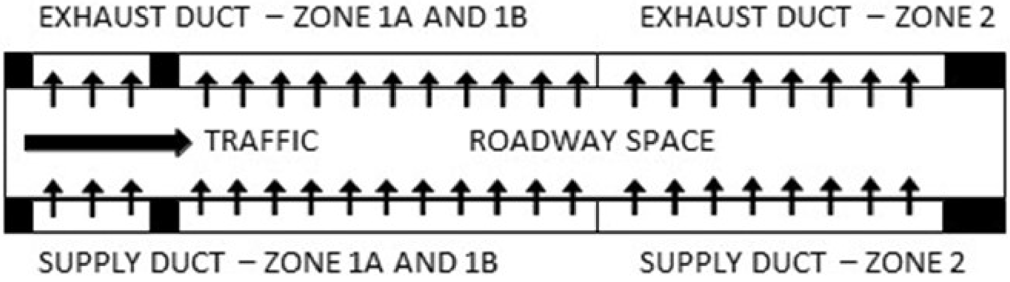


Figure 5-35: Transverse ventilation system schematic.

For fire scenarios, with unidirectional traffic, a combination of supply and exhaust zones are operated to achieve the greatest possible longitudinal flow (in the direction of travel) at the fire location. In unidirectional traffic the main goal is to achieve critical velocity. Each unique operation of supply and exhaust zones is defined as a mode of operation.

The schematic from Figure 5-35 is used to demonstrate typical modes of operation. The first mode of operation uses all fans in exhaust to generate airflow. Figure 5-36 shows a schematic of the mode and fan operations, and Figure 5-37 shows the resultant velocity profile. The system can achieve a longitudinal velocity that is positive (positive air velocity in the example represents flow in the same direction as vehicle travel) and greater than 600 fpm (an order of magnitude value of the critical velocity for a large heavy goods vehicle fire) for about one third of the length; from STA 975 to approximately STA 3000. Beyond this location the velocity decreases and eventually the airflow changes direction such that, if a fire were to occur near the tunnel exit, say at STA 7000, and this mode were used, smoke would be drawn back over vehicles upstream. This demonstrates why different modes of operation are needed.

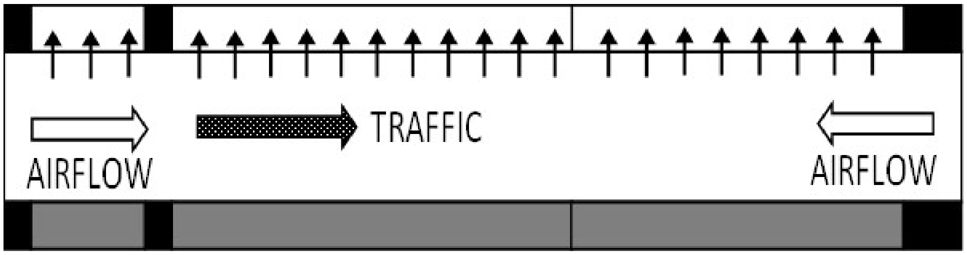


Figure 5-36: Transverse ventilation system schematic, all exhaust mode (1).

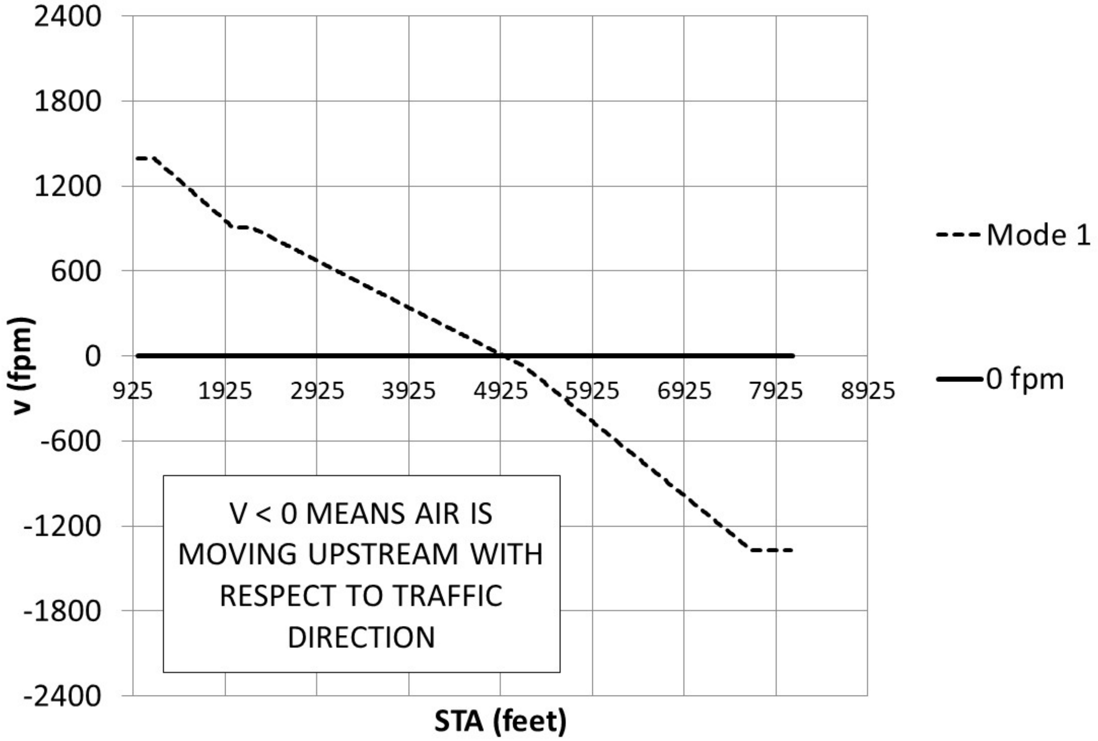


Figure 5-37: Graph. Transverse ventilation system schematic, all exhaust mode (1).

The second mode of operation uses a combination of supply and exhaust fans to generate airflow. Figure 5-38 shows a schematic of operation and Figure 5-39 shows the resultant velocity. Note that the velocity is less than 600 fpm for most of the tunnel when using this mode (between STA 3000 and STA 5000). This is a typical result that occurs with most transverse systems which have regions of the tunnel where airflow capacity is not sufficient to achieve necessary velocity. Like the example above, if this mode were used inappropriately, say near to the tunnel entry at STA 1000, then smoke would be blown back over vehicles upstream.

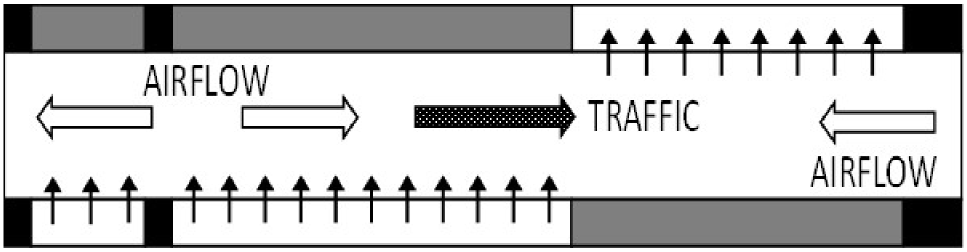


Figure 5-38: Transverse ventilation system schematic, supply and exhaust mode (2).

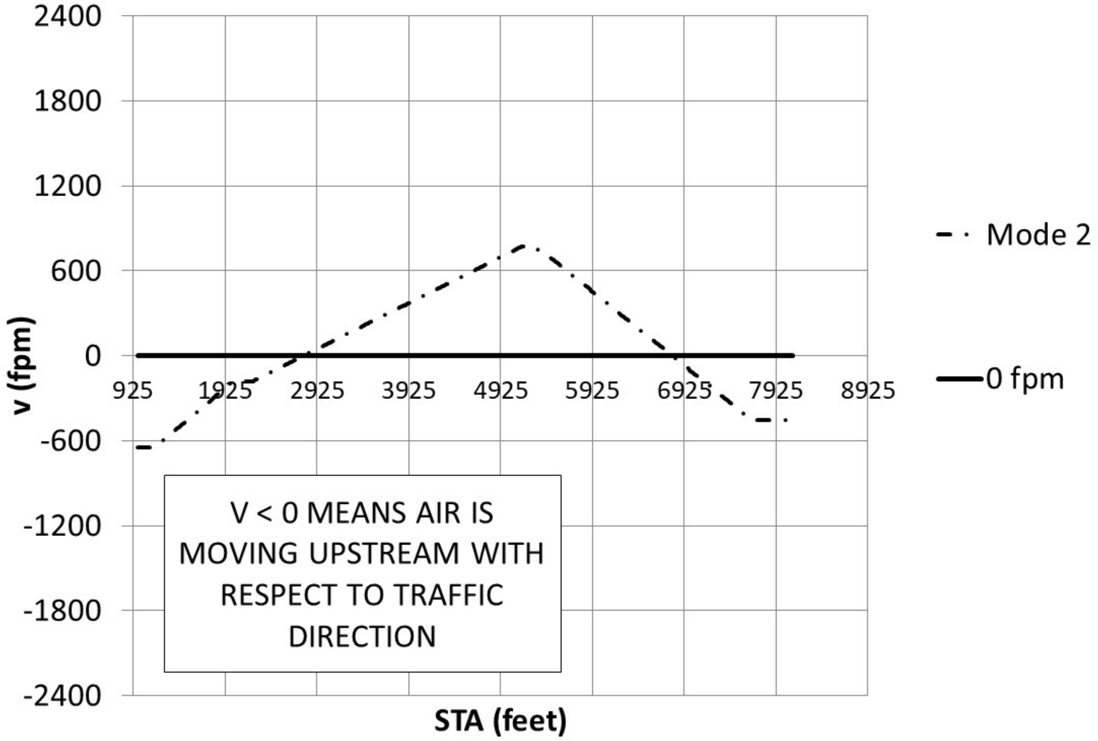


Figure 5-39: Transverse ventilation system schematic, supply and exhaust mode (2).

Figure 5-40 shows the third mode of operation which uses the supply air duct to generate a longitudinal velocity. Figure 5-41 shows a graph of velocity achieved. This mode would be used for STA 5000 (approximately) up to the tunnel exit. The airflow in this scenario is close to 600 fpm.

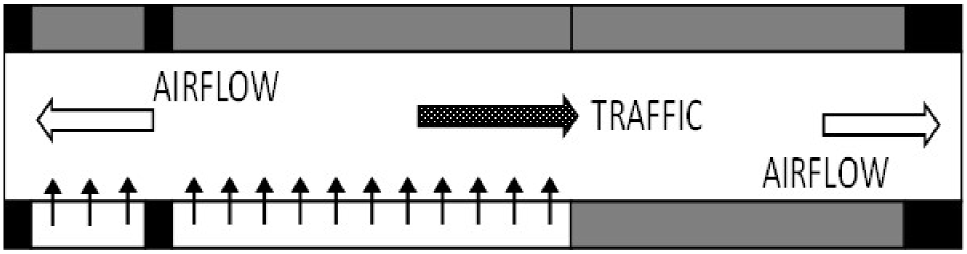


Figure 5-40: Transverse ventilation system schematic, supply mode (3).

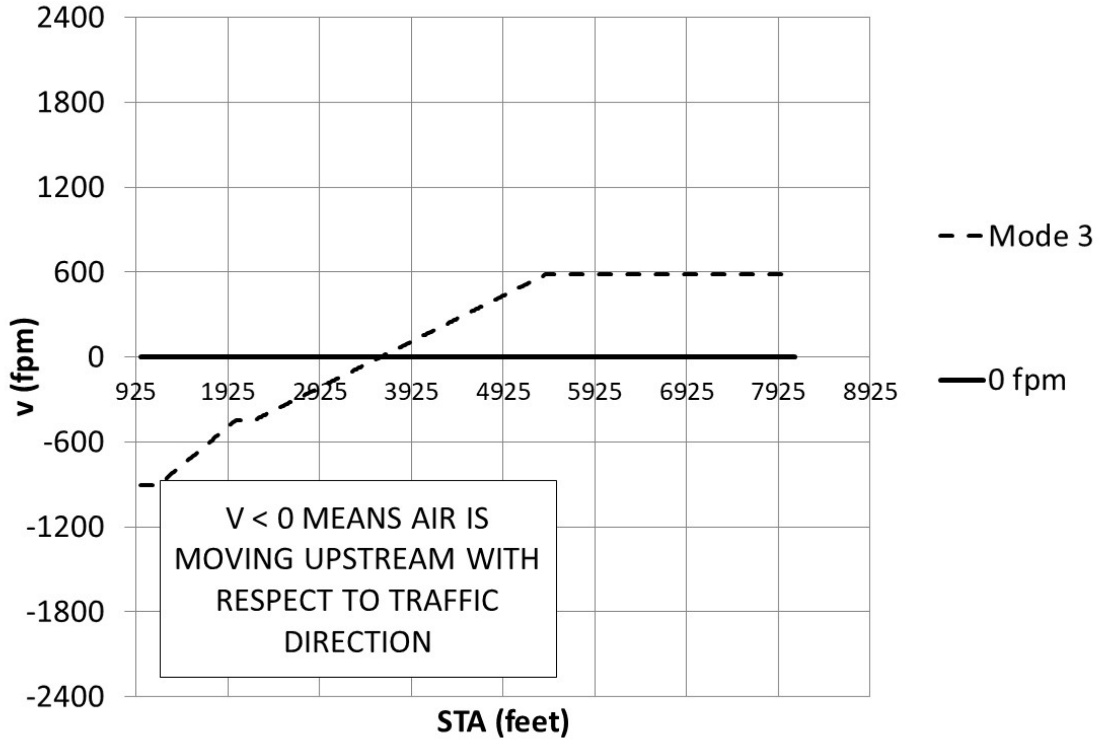


Figure 5-41: Graph. Transverse ventilation system schematic, supply mode (3).

Per NFPA 502 Section 11.2.4(2)(b), the principal goal of operation of the system in unidirectional traffic mode is to *create a longitudinal airflow in the direction of traffic flow by operating the upstream ventilation zone(s) in maximum supply and the downstream ventilation zone(s) in maximum exhaust.* As noted above, the nominal critical velocity is 600 fpm for a large heavy goods vehicle fire and the system should be able to control the smoke at locations where this velocity is achieved. CFD results have demonstrated this to be the case [147].

Considerations related to fan operations are necessary for a transverse system. Pressure drop in the duct network dominates losses, however, care must be taken to adequately account for tunnel side pressure losses due to wall friction, vehicles and the fire. Also, the fans might experience elevated temperatures and the impact of the elevated temperatures on the fan performance must be factored in if this is likely to be an issue. It is necessary that the designer have not just the system curve but also the fan curve. The fan laws can be used to estimate the impact of the elevated temperature on fan performance.

Figure 5-42 shows an overlay of air velocity in the tunnel for the three modes, with highlighting used to demonstrate the locations in the tunnel where each mode would be applied should a fire occur in that location.

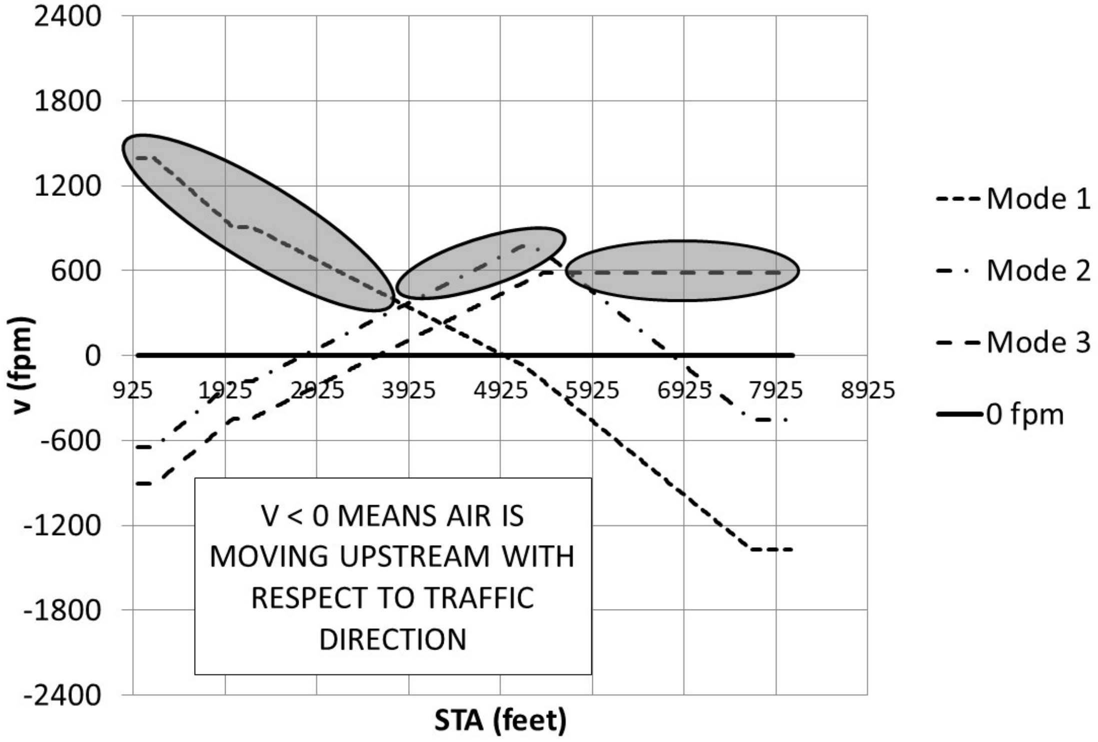


Figure 5-42: Graph. Combined velocity chart showing where each mode is optimal.

Another type of transverse ventilation includes semi-transverse systems with single point exhaust. This system has recently been implemented in the Alaska Way Tunnel in Seattle. Operable dampers are used and a damper downstream of the fire is opened to extract smoke. This system has also been implemented in tunnels in Brisbane, Australia. Figure 5-44 shows the concept. In this system, the same principles as a fully transverse system apply; the magnitude of the upstream velocity with respect to critical velocity will be the determinant of smoke control. The system needs to be sized to exhaust the airflow from upstream, plus some additional airflow from downstream to mitigate smoke overshoot. Previous Australian tunnel projects have required at least 60 fpm from downstream of the fire.

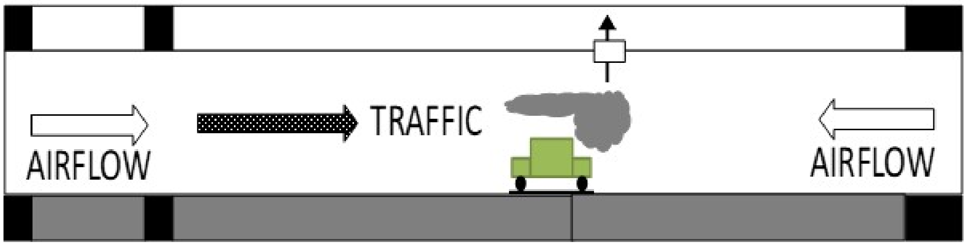


Figure 5-43: Point exhaust schematic.

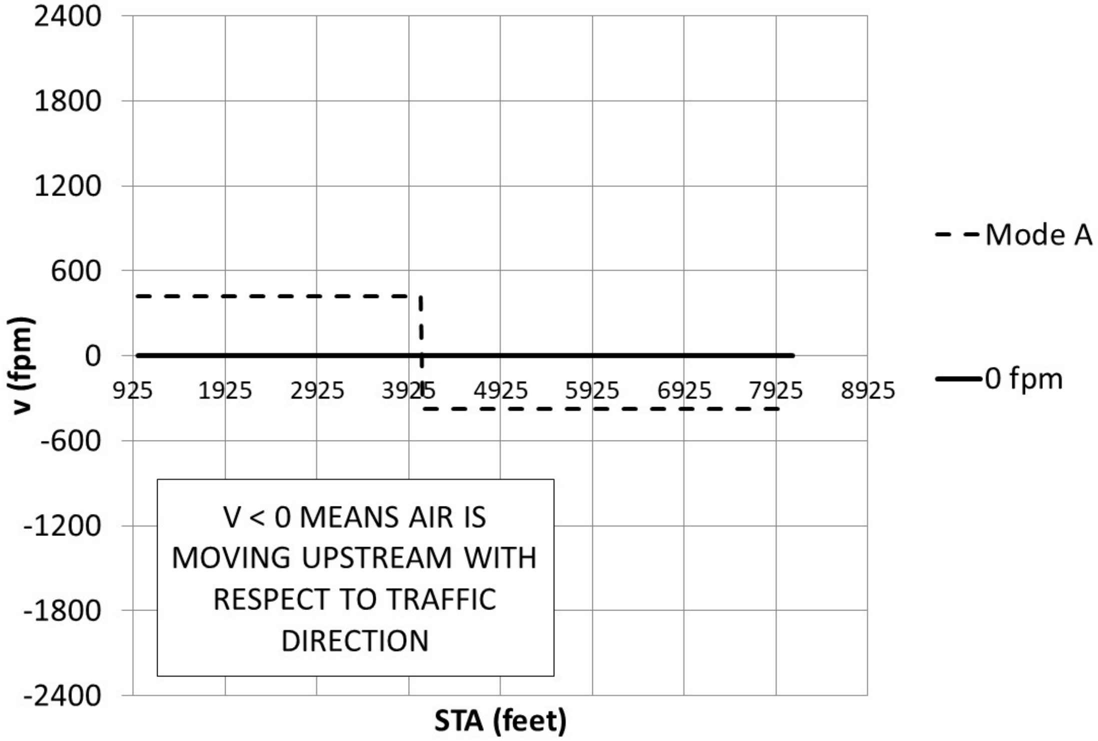


Figure 5-44: Graph. Single point exhaust system schematic.

Considerations for interaction of a transverse ventilation system with an FFFS are like that of a longitudinal EVS. In general, the system will see improved performance due to cooling and hence a decreased amount of heat and combustion products to manage. However, transverse systems can introduce unique considerations such as the interaction of droplets with the exhaust ports. Deluge nozzles in proximity to the ceiling (exhaust) vent openings will be exposed to the concentrated exhaust airflow from the tunnel. Deluge nozzles and piping will be cooled by the large volume of water flowing through the pipes. However, mist systems use much lower water volumes and may not receive the same level of cooling, possibly damaging the pipework. Water droplets could be entrained in to the exhaust airstream and not delivered to the tunnel roadway space. In addition, the nozzle and pipework can interfere with the exhaust airflow. CFD analysis is one tool that can be considered to investigate this effect.

Most of the older road tunnels in the US have a transverse ventilation system. Consideration to retrofit these tunnels with an FFFS introduces several challenges. For example, the FFFS pipework (branch and main) will likely need to be installed within the exhaust duct above the roadway, where it will increase air flow resistance. This will then reduce the total airflow and perturb the balanced delivery of air through the tunnel. Steps should be taken when considering FFFS retrofits in tunnels with transverse ventilation systems, including:

A. Survey existing system – Fan curves for the installed fans are needed. If the fan data are reliable, speed measurements for the fan wheel can be used to determine, via the fan laws, the current system performance (pressure drop, fan airflow). Measurements of airflow and pressure at around 10 locations along the exhaust air ducts, are necessary to verify the duct balance and to obtain the current duct friction factor.
B. Pressure loss calculation and fan curves – A calculation is necessary for pressure losses in each exhaust duct using spreadsheet analysis, calibrated against the measurements from step A. The fan curve needs to be incorporated into the calculation and the fan operating point verified with respect to the design basis and measurements (from step A). The relative pressure loss in each major airflow segment (duct, transition to building, building and discharge) is needed to develop the calculation.
C. FFFS friction calculation and air balance impact – The additional duct friction losses caused by the inclusion of FFFS components (nozzles and piping plus water spray) needs to be computed and incorporated into the calculation from step B to estimate the impact (reduction) on the exhaust duct airflow. Impact on the air duct balance should also be computed at this step. If the airflow balance is affected too severely (airflow no longer uniform through exhaust ports) it will be necessary to rebalance the exhaust duct. New plate settings might need to be determined.
D. In-tunnel airflow impacts – Analysis (1D cold flow) is conducted to determine the before and after in-tunnel velocity (i.e. before and after the FFFS inclusion). From this cold flow analysis, it is possible to identify the locations where the airflow reduction due to FFFS has the greatest impact. CFD analysis of the before and after smoke management outcomes may be needed for the affected locations. Analysis of cases after the FFFS inclusion also need to factor in the cooling provided by the FFFS, as well as the sensitivity of outcomes for a scenario where the FFFS does not operate. Results to report include the smoke spread contour plots and temperature contour plots. Results need to be assessed relative to the pre-FFFS situation and in line with NFPA 502.
E. AHJ acceptance – The results from step D need to be presented to the AHJ for their acceptance. If results are not acceptable it may be necessary to explore options to increase fan capacity, such as running fans at a higher speed. However, this option is generally not feasible because a fan speed increase creates additional power needs.

Semi-transverse ventilation systems with single point extract (refer Figure 5-5) are a combination of a longitudinal ventilation system and a transverse system. Information on the upstream velocity necessary to control smoke with FFFS is as per the discussion in Section 5.3.2. A lower upstream velocity will also translate to a reduced smoke exhaust rate since there will be a proportionally reduced airflow rate. CFD analysis is necessary to confirm the efficacy of a reduced exhaust rate.

5.3.10 Natural Ventilation

In a natural ventilation scheme the airflow is subject to external wind. Natural ventilation is typically only applied on short tunnels (1000 ft. or less in length) where egress and fire fighter access can be achieved without mechanical ventilation. Natural ventilation can be useful in situations where there is a construction phase with bidirectional traffic. The principles for analysis of natural and mechanical ventilation are outlined in Section 5.3.8.

5.3.11 Integrated System Operation

One important factor to consider with an integrated EVS-FFFS design is system operation. This consideration involves the question of when should only the EVS be used, only the FFFS, or when both systems should be operated together:

- If the EVS-FFFS design has been fully integrated, then it will be essential to operate both systems simultaneously, since the EVS likely depends on the FFFS cooling to achieve the design goals. Note that if tenability is dependent on both the EVS and the FFFS operating, redundancy must be considered (e.g. n+1 ventilation fans or restricting vehicle access to light vehicles only if the FFFS is not operational).
- Operationally, tunnels in Australia and New Zealand have a policy of activating the FFFS once a fire is confirmed and once traffic has been instructed to stop [15]. Ventilation may be started earlier since it has minimal impact on traffic.

Situations may arise where the EVS operation is delayed or the FFFS operation is delayed (e.g. traffic stop signals not sent or the fire is ‘small’ and does not warrant FFFS use). Such situations are not common and in most cases, the operational response is not complicated by asking an operator to make such specific decisions when it involves deciding whether to use the FFFS [15].

5.4 Summary

Questions raised in the initial phases on the FFFS-EVS integration are outlined below, along with comments on the findings of the literature survey and synthesis.

What is the deflection of water droplets by the EVS?

Generally, not a concern, if multiple zones can be activated, refer to Section 5.3.7. A validated modeling methodology for water spray drift would be useful.

Is there a critical velocity equation that is applied when the FFFS are applied?

One equation has been derived, based on test data, refer to Section 5.3.2. Figure 5-19 provides a correlation but the FHRR is limited to a maximum of 40 MW. For FHRRs greater than 40 MW, there is no specific equation for critical velocity with FFFS applied, and it is necessary to use CFD modeling or testing.

Where are the vulnerable points in an integrated FFFS-EVS design?

Research needs due to vulnerability include:

- Develop a more general equation for critical velocity with ventilation and FFFS using CFD modeling.
- Pressure loss caused by the FFFS components and FFFS spray (droplets and humidity) – investigate with testing and analytical sums
- Pressure loss caused by the fire when an FFFS is operating.
- FFFS impact on FHRR – agree on a nozzle type and water application rate for a certain FHRR outcome.
- In terms of tenability for occupant egress, further information would be useful as follows:
  - Additional data on HGV toxic gas yields.
  - Measurement of irritant species for a fire with and without FFFS.
  - Timing for egress, FFFS activation, fire growth, etc.

6 FFFS AND TUNNEL STRUCTURE

This section addresses the requirements of NFPA 502 that deal with protecting the tunnel structure from collapse as result of a fire. This section also reviews methods for assessing fire dynamics and the subsequent thermal conditions, which should be considered in a structural design. The impact of FFFS and passive fire protection methods are also reviewed. This section does not address structural design and the impact of elevated temperatures on structural integrity. To address this an in-depth consideration of structural design beyond the scope of this present work. For an example and more detail on the impact of elevated temperatures, refer to the NCHRP Highway Bridge Fire Hazard Assessment document [148].

6.1 NFPA 502 Structural Protection Requirements

The extreme temperatures possible in a tunnel fire can extensively damage a tunnel's structure. This is recognized in NFPA 502 [12], which requires that the structure be protected against progressive structural collapse, and if provided with structural fire protection material, concrete temperatures are not to exceed specified limits. Unless another time-temperature curve is approved by the AHJ, NFPA 502 requires the structure be able to withstand the Rijkswaterstaat (RWS) curve [12] (refer to Figure 6-1). The requirement is challenging due to the high peak temperatures of 2460°F (1350°C), and the prolonged exposure of 120 minutes with temperatures at 2190°F (1200°C) or more. When a thermal protective board or other thermal insulation is provided, NFPA 502 requires that the concrete surface temperature is kept to less than 715°F (380°C), and beyond this temperature, there is a risk of major spalling [12] [149].

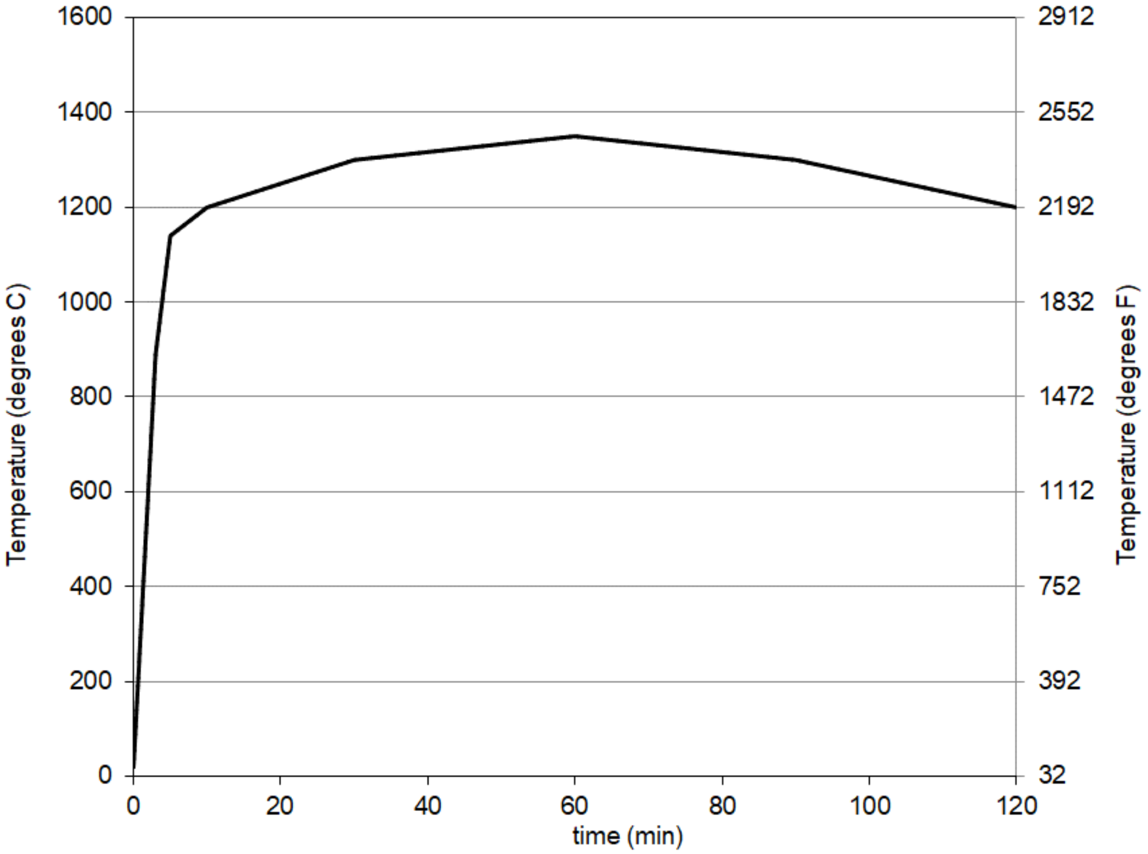


Figure 6-1: Graph. RWS fire curve [12].

As an alternative to applying the RWS fire curve NFPA 502 allows for an engineering analysis to be conducted to determine a suitable time-temperature curve [12] (refer to Section 6.3.2 herein). If permitted by the AHJ, this engineering analysis can include a performance-based approach, where the fire load (based on vehicles using the tunnel and their cargo) and benefits of the FFFS are accounted for in the development of a design basis time-temperature curve. The water spray generated with an FFFS has a well-established ability to both reduce the FHRR and the resultant temperatures [150] [151]. This leads to potential benefits in reduced structural damage, products of combustion, and smoke produced by the fire. Accounting for this benefit might result in a reduced need for certain structural thermal protection measures, such as protective boards or spray-on fire proofing. Specific requirements of NFPA 502 related to structural protection are summarized in Table 6-1.

Table 6-1: NFPA 502 structural durability requirements [12].

NFPA 502 Section	Extract	Comment
7.3.1	Regardless of tunnel length, acceptable means shall be included within the design of the tunnel to prevent progressive collapse of primary structural elements in accordance with this standard to achieve the following functional requirements in addition to life safety: (1) Support fire fighter accessibility (2) Minimize economic impact (3) Mitigate structural damage	The primary goal of the durability analysis is to provide assurance that structural damage is prevented or minimized. Achieving this will also support items (1) and (2).
7.3.2	The structure shall be capable of withstanding the temperature exposure represented by the Rijkswaterstaat (RWS) time-temperature curve or other recognized standard time-temperature curve that is acceptable to the AHJ, following an engineering analysis as required in Chapter 4.	An alternative time-temperature curve may be proposed based on the RWS but considering the limited cargo types allowed and the benefit of the FFFS.
7.3.3	During a 120-minute period of fire exposure, the following failure criteria shall be satisfied: (1) Regardless of the material the primary structural element is made of, irreversible damage and deformation leading to progressive structural collapse shall be prevented. (2)* Tunnels with concrete structural elements shall be designed such that fire-induced spalling, which leads to progressive structural collapse, is prevented.	Item (1) is the focus of the analysis. Spalling is a concern, but provided it does not lead to progressive collapse, some minor spalling can be acceptable.
7.3.4	Structural fire protection material, where provided, shall satisfy the following performance criteria: (1) Tunnel structural elements shall be protected to achieve the following for concrete: (a) The concrete is protected such that fire-induced spalling is prevented. (b) The temperature of the concrete surface does not exceed 380°C (716°F). (c) The temperature of the steel reinforcement within the concrete [assuming a minimum cover of 25 mm (1 in.)] does not exceed 250°C (482°F).	This section applies only to situations where specific fire-proofing material will be used. The temperature requirements are prescriptive in nature. If higher temperatures are found to be structurally acceptable then a quantitative assessment may be provided for AHJ approval.

6.2 Review of Incidents and Test Data – Structural Focused

Catastrophic fire incidents have occurred in highway tunnels, in terms of structural and human impact. A fire in the Tauern Tunnel in 1999 caused significant structural damage including spalling and structural collapse [152]. The fire involved 24 cars and 16 trucks. The spalling was extensive and affected both the tunnel ceiling and the sidewalls. Other examples of catastrophic fire events with significant damage include the Mont Blanc Tunnel fire in 1999 (900 m of damage and closure for three years), and the Newhall Pass fire in 2007 (severe damage to the structure) [10]. Most incidents with major damage have involved heavy goods vehicles [10].

In contrast to these events, the Burnley Tunnel fire in 2007 provides an example of the mitigation potential of an FFFS. The fire involved HGVs and had potential to cause major structural damage. The tunnel's FFFS successfully operated; there was minimal damage and the tunnel quickly reopened to traffic. The FFFS provided fire suppression in this incident and the system performance was good enough to mitigate major damage as a result of this fire [81] [80]. This incident caused the industry to further reconsider the use of FFFS as it showed firsthand that an FFFS had potential to mitigate structural damage and enable faster recovery of the infrastructure following an incident.

Full-scale fire test data from the LTA tests were used to develop alternative fire curves for a scenario with FFFS operating [153]. In these tests the free-burn FHRR was 150 MW, while the suppression cases kept the FHRR to less than 100 MW. The results were based on a water application rate of 0.30 gpm/ft^2 (12 mm/min). Temperature measurements were made using a plate thermometer; the resultant peak temperatures were determined to be 1300°F (700°C). Additional test data or model results are necessary for cases with a different water application rate.

As noted in Section 3.5, CFD can be used to predict cooling due to an FFFS. The results of this analysis can then be used to help develop an alternative time-temperature curve for structural design. Two example studies of ceiling and wall temperatures during a fire event with FFFS operation include the following:

- A modified time-temperature curve for the structure, based on inclusion of an FFFS, was developed using results from CFD simulations [150]. The authors argue that a reduction of the FHRR from 200 MW to 100 MW is reasonable for a tunnel with an FFFS included. A significant reduction in ceiling temperature is reported based on model results.
- CFD analysis was used to investigate wall temperatures for a large heavy goods vehicle fire of 100 MW [151]. Like previous studies, analysis showed that the heat-affected area of tunnel was greatly reduced when the FFFS was operated. A model of tunnel spalling was also included, and the area of damage to the tunnel was vastly reduced when the FFFS was included.

Previous incidents have shown the significant impact that a major fire can have on the tunnel; in terms of life safety and tunnel structure. An extended closure period from a fire can have major long-term economic impacts. Taking advantage of the FFFS for structural fire protection is still under development in the industry:

- International Tunneling Association Guidelines on structural fire protection for road tunnels does not explicitly recognize structural fire protection with FFFS [149].
- A 2016 PIARC report on FFFS notes that FFFS may be recognized as a compensatory measure and that passive fire protection, in some situations, could be reduced as a result [11]. Reliability of the FFFS is identified as a critical consideration in these cases.

6.3 Structural Fire Protection Analysis

6.3.1 Overview and Interfaces

Key steps in the design process depend on the structural protection method used. Mitigation methods typically include the following [149] [154]:

- Provide a protective board or spray-on material to insulate the concrete (or structure) from heat.
- Include polypropylene fibers in the concrete mix to mitigate major spalling and conduct analysis to provide assurance the structure has sufficient strength at elevated temperatures.
- Provide a layer of sacrificial concrete.

With any method of structural design, analysis of the fire protection requirements first needs a determination of the FHRR. This should consider the anticipated fuel load and any reduction in FHRR from application of water spray. Also necessary are a determination of an appropriate time-temperature curve specific to the types of vehicles permitted in the tunnel, and a determination of resulting temperatures at the concrete surface and at reinforcement depth.

A critical element in the analysis is the development of a time-temperature curve [150]. The RWS curve noted in NFPA 502, Figure 6-1, describes a fire scenario for the largest expected fuel load in a road tunnel (considering any vehicle access restrictions), generally a heavy goods vehicle fire with regular cargo or a liquid fuel tanker. The curve does not take into consideration the benefits of a FFFS. Research has shown that FFFS can produce a reduced-severity time-temperature curve [151] [153] [66].

The design FHRR is the determining factor in how temperatures in the tunnel develop over time. Numerous full-scale tunnel fire test programs have occurred in recent years, primarily on HGV fuel loads. Section 3.4.3 provides an overview of the testing and resultant FHRRs. To produce the RWS curve, in terms of temperature and duration, the fuel load must be equivalent to that of a fuel tanker. RWS temperatures can be reached using a relatively less severe commodity such as wood pallets, though the temperatures cannot be maintained for the same duration [59].

In general, the RWS curve can be assessed relative to the vehicle types allowed and used as a baseline in generating an alternative time-temperature curve. The aim is to determine fuel load appropriate to the vehicles using the facility and then assess the magnitude of fire that could be sustained; in terms of temperature and duration. The fire duration will depend on the total fuel available as well as the design FHRR profile. These properties then guide development of the time-temperature profile.

CFD simulations can be employed to show typical temperatures with and without FFFS for a given FHRR profile [150] [151]. The difference in temperature (before and after) and the potential fire duration (considering available fuel load) can be used to derive a time-temperature curve that accounts for the benefits of an FFFS. Note that CFD models based on a volumetric heat source should not be used for this purpose as those models can over or under predict temperature if a non-physical fire volume is used [151].

Figure 6-2 outlines the typical design process. Step 1 is the primary focus of this review and this is typically conducted by a fire safety engineer. Steps 2 and 3 need interfacing with the structural engineer. There needs to be a clear understanding and communication between the two disciplines to provide assurance that analysis results are used appropriately. Some aspects of this interfacing are discussed further herein.

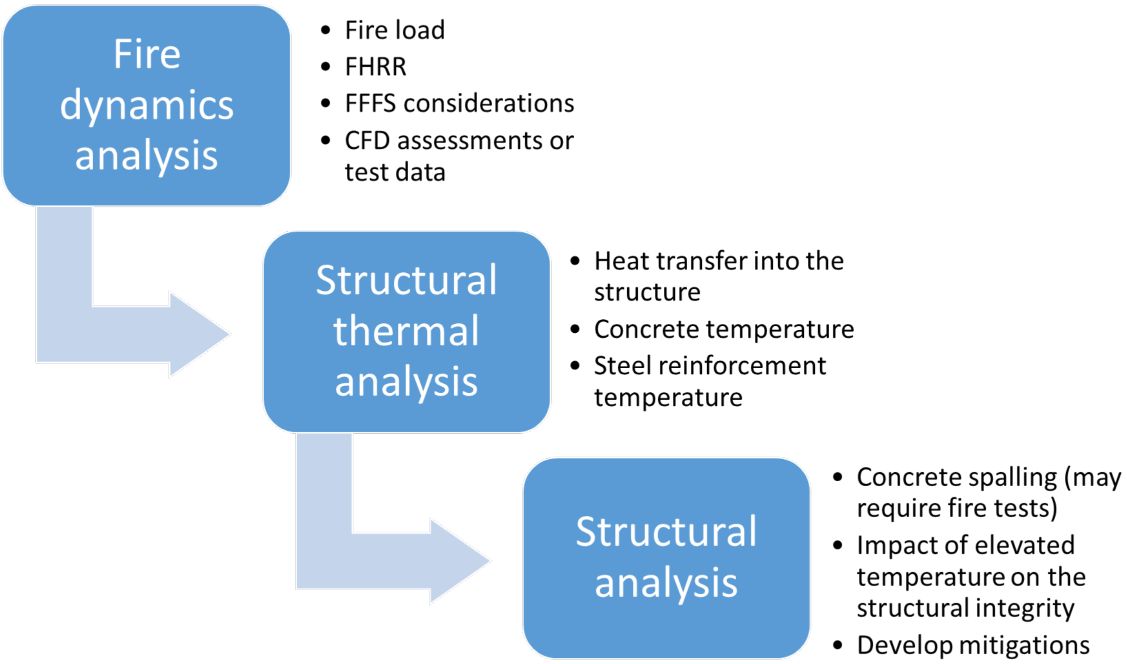


Figure 6-2: Structural fire protection design process.

6.3.2 Fuel Loads and Time-Temperature Curves

When developing a performance-based time-temperature analysis, considering the vehicle fuel load will help quantify the fire duration. Considerations are made below with respect to hazardous goods vehicle fires versus a typical heavy goods vehicle fire.

Hazardous materials constitute a class of cargos that include bulk transport of dangerous and highly flammable materials. Liquid fuel tankers fall into this category and are considered to contain the greatest potential fire loads in the tunnel environment [12]. The RWS curve is the most severe time-temperature curve provided in NFPA 502. The standard does not provide specific information as to what vehicle type or size could produce the RWS time-temperature curve, but the annex does give FHRR information using vehicle types (see Table 6-2). Table 6-3 provides an analysis of a tanker fire duration and it shows the fire could last for two hours or more. In contrast, a heavy goods vehicle fire, based on the Runehamar fire test, has a shorter duration. Note that this calculation is based on multiple assumptions, including a constant FHRR and conditions for well ventilated combustion. This type of calculation should be treated as an approximation.

In addition to fire duration, the second component needed to define a time-temperature curve is the fire temperature. A natural gas flame has a temperature in the order of 1150°C to 1250°C. Typically the flame temperature of a large pool fire is slightly less, at around 1100°C to 1200°C [155]. The Runehamar tests [59] showed that a heavy goods vehicle fire load can generate similar temperatures, around 1200°C to 1300°C (see Figure 6-3). However, based on the test data and assessment in Table 6-3, those peak temperatures are likely to persist for a shorter duration than a liquid fuel fire. Note that a single vehicle fuel load is considered here; if multiple (adjacent) vehicles are involved then it is possible that the direct fire effects would be seen at adjacent locations on the structure. The involvement of multiple vehicles might cause a slightly longer effective fire duration since the adjacent vehicles would preheat the structure above the secondary vehicles. Multiple fires at different locations is not typically considered.

Table 6-2: Fire data for typical vehicles [12].

Vehicles	Peak HRR (MW)	Time to peak HRR (min)
Passenger car	5-10	0-54
Multiple passenger car	10-20	10-55
Bus	25-34	7-14
Heavy goods truck	20-200	7-48
Flammable/ combustible liquid tanker	200-300	Not available

Table 6-3: Analysis of fire duration (single vehicle only).

Parameter	Tanker	Source	HGV	Source
Mass or volume of fuel	Typical tanker load max 47,600 kg	Web search, order of magnitude value	11,010 kg	[59]
Density	740 kg/m^3	[156]	N/A	
Fuel heating value	43.7 MJ/kg	[156]	22.1 MJ/kg	Calculated
Energy load	2080 GJ	Calculated	244 GJ	[59]
Peak FHRR	Not available	Not applicable	202 MW	[59]
Average FHRR	300 MW	Assumed	91 MW	Calculated
Fire duration	**115 minutes+**	Calculated	**45 minutes+**	[59]

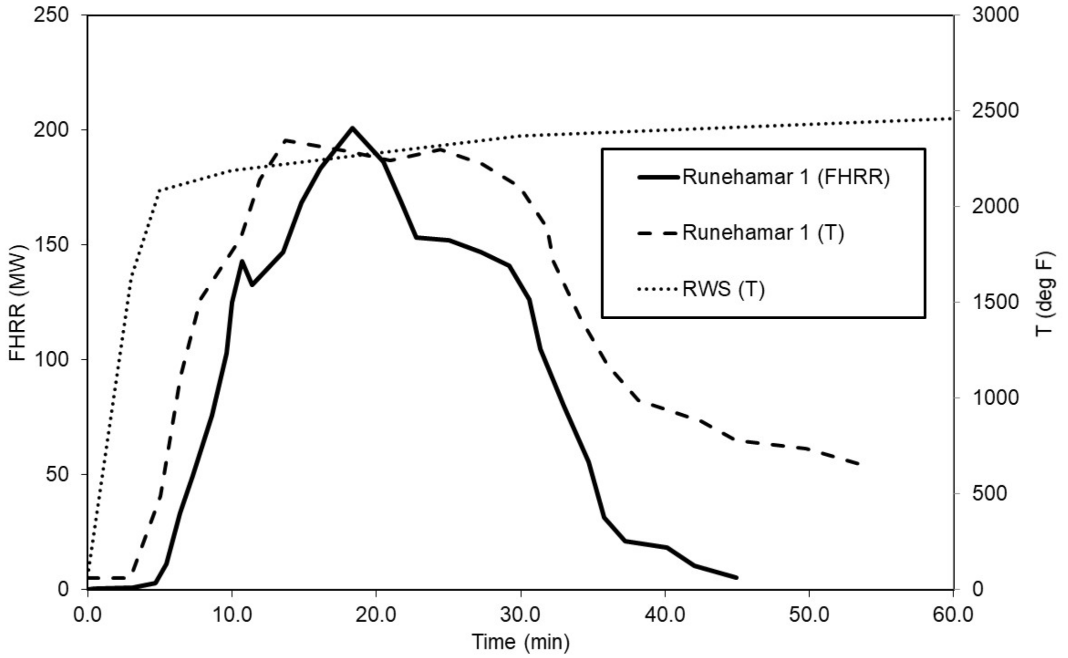


Figure 6-3: Graph. Runehamar fire test FHRR and temperature comparison with RWS curve [12] [41].

6.3.3 Fire Heat Release Rate

Peak flame temperatures are independent of the FHRR. However, in development of the temperatures in a time-temperature curve, it is important to account for the FHRR because this ultimately defines the total heat load that the structure will see. Section 3 provided a review of FFFS impact on the FHRR. Some aspects of that review are revisited herein.

A summary of FHRR performance from three recent test programs [3] [2] [4] is shown in Table 6-4. Tests where fuel loads were shielded from water spray provide the most useful data, as these are the most challenging vehicle fires. Fuel loads that are largely enclosed are not considered as these may limit fire size by oxygen starvation. Review of these full-scale test programs shows consistent performance of the FFFS in reducing the FHRR by as much as 50%. The exact FHRR reduction depends on many factors including the water application rate, fire load and configuration, fuel geometry, and nozzle type. While many combinations of solid fuel source and geometry exist, experimental tests have consistently shown that FFFS can generally halt an increase in the FHRR, or even lower the FHRR to some degree.

An important factor regarding the FHRR is the impact of FFFS on a liquid fuel fire. Liquid fuel has a lower density than water and the fuel can float on top of water. Tests were conducted on a spill fire in a configuration that mimicked a sloping road [5]. It was found that water application did not exacerbate the FHRR, but it did not provide fire suppression unless a foam additive was included in the water. Water application rates of 0.12 gpm/ft^2 (5 mm/min) and 0.25 gpm/ft^2 (10 mm/min) were tested. A water application rate of 0.25 gpm/ft^2 (10 mm/min) with foam added was necessary to provide a reduction in the FHRR. This is an important result; it means that FFFS will not have a major mitigating effect for a gasoline tanker fire where spilled fuel is involved. The impact of this on structural fire protection is that a passive protection solution, such as a board or spray, is almost certainly necessary. It is noted that many tunnels ban dangerous goods vehicle passage.

Table 6-4: Summary of Runehamar [3] [135] (RH) and LTA [4] full-scale test programs.

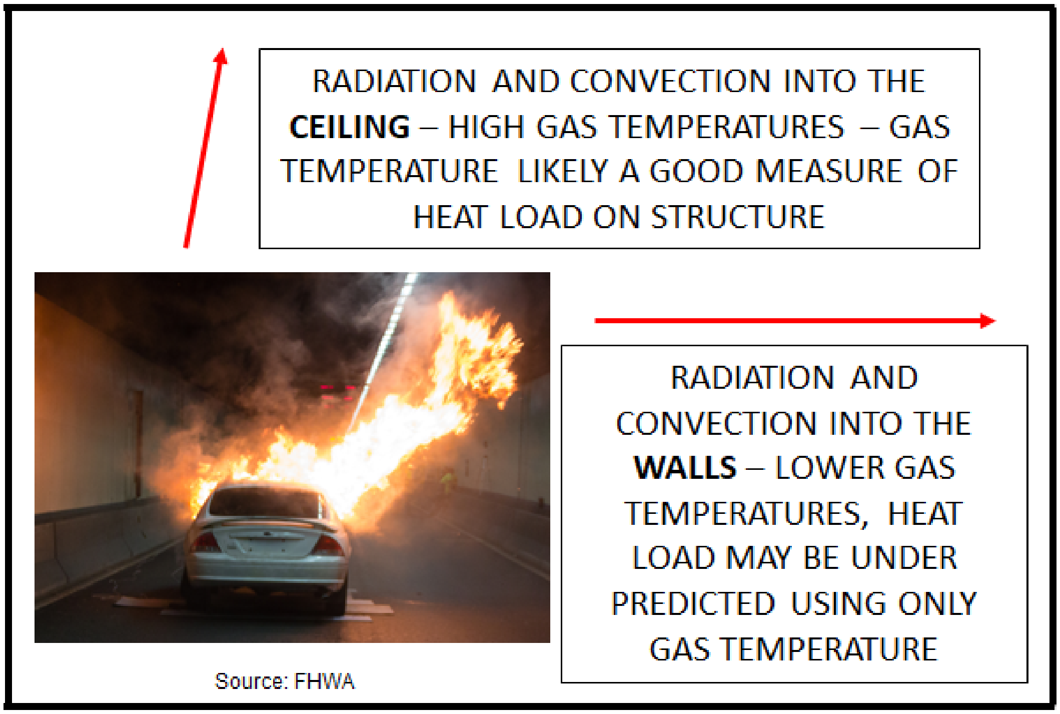
Test ID	**Nozzle type**	**Total fuel energy (GJ)**	**Total fuel energy burned (GJ)**	**Max. HRR (MW)**	**% HRR reduce**	**% fuel energy burned**	**Water rate (gpm/ft^2)**	**Time FFFS on (min)**
RH 13-1	TN-25 (sidewall)	189	36.4	**17.7**	78	0.19	0.25	6:04
RH 13-2	TN-25	189	32.0	**18.5**	77	0.17	0.25	8:20
RH 13-3	TN-25	189	27.0	**15.2**	81	0.14	0.25	13:18
RH 13-4	TN-25 (tarpaulin)	189	37.5	**11.0**	86	0.20	0.25	18:25
RH 13-5	TN-25 (no steel cover)	189	54.7	**39.6**	50	0.29	0.25	7:17
RH 13-6	TN-25 (free burn)	189	180.8	**78.9**	Not available	Not available	Not available	Not available
RH 16-1	TN-25	189	33	**14.9**	81	0.17	0.21	8:16
RH 16-2	TN-17	189	49	**13.9**	82	0.26	0.18	8:15
RH 16-3	TN-17	189	45	**16.5**	79	0.24	0.16	8:12
RH 16-4	TN-25	189	23	**14.0**	82	0.12	0.18	8:47
RH 16-5	SW-24	189	78	**29.7**	62	0.41	0.16	8:33
RH 16-6	SW-24 (bulb, 93°C activation)	189	75	**31.1**	61	0.40	0.09 to 0.12	5:40
LTA 1	Directional (down)	≈100	46.6	**37.7**	75	Not available	0.30	4:00
LTA 2	Directional (down)	≈100	52.7	**44.1**	71	Not available	0.20	4:00
LTA 3	Standard	≈100	44.5	**44.4**	71	Not available	0.30	4:00
LTA 4	Standard	≈100	35.9	**29.5**	80	Not available	0.30	4:00
LTA 5	Standard	≈100	30.2	**27.1**	82	Not available	0.30	4:00
LTA 6	Standard	≈100	61.6	**97.5**	82	Not available	0.30	4:00
LTA 7	Free burn	≈100	99.2	**150**	N/A	≈100	N/A	N/A

6.3.4 Fire Dynamics Analysis

As noted in Section 3.5, CFD can be used to predict the cooling effects of an FFFS. The main input needed for this analysis is the FHRR profile (time and duration). The FHRR profile is informed by consideration of the fuel load (total energy available) and the FFFS fire control potential. An example CFD package used for prediction of the temperature field due to an FFFS is the Fire Dynamics Simulator software [151] [125].

Numerous other input parameters are needed for a CFD model of the FFFS and tunnel environment during a fire. Parameters related to the FFFS include the droplet diameter, water application rate, spray pattern, and droplet velocity [125]. It is often difficult to equate a system's nozzle parameters with these inputs and nozzle spray pattern data are not routinely published. The solution in this case is to conduct sensitivity analysis to verify that uncertain parameters do not substantially change a key result.

Another key consideration in the use of a CFD model (or full-scale test data), is the interpretation of the results. Gas phase temperatures near the solid surface may not always accurately reflect the total heat load on the structure when there is also a substantial radiative heat component. Figure 6-4 shows an example situation where gas temperatures alone can under-predict the heat load on the structure. The adiabatic surface temperature (AST) concept was developed to overcome this [157]. The AST is the temperature of a surface that cannot absorb or lose heat to the environment; the surface is a perfect insulator. It is based on the heat transfer to the surface by radiation and convection [157]. The AST can be approximately measured with a plate thermometer [157] and this has been successfully used in full-scale fire tests where FFFS were employed [153]. An example time-temperature curve based on full-scale testing is provided in Figure 6-5.



RADIATION AND CONVECTION INTO THE **CEILING** – HIGH GAS TEMPERATURES – GAS TEMPERATURE LIKELY A GOOD MEASURE OF HEAT LOAD ON STRUCTURE

RADIATION AND CONVECTION INTO THE **WALLS** – LOWER GAS TEMPERATURES, HEAT LOAD MAY BE UNDER PREDICTED USING ONLY GAS TEMPERATURE

Source: FHWA

Figure 6-4: Heat transfer to the walls of a structure.

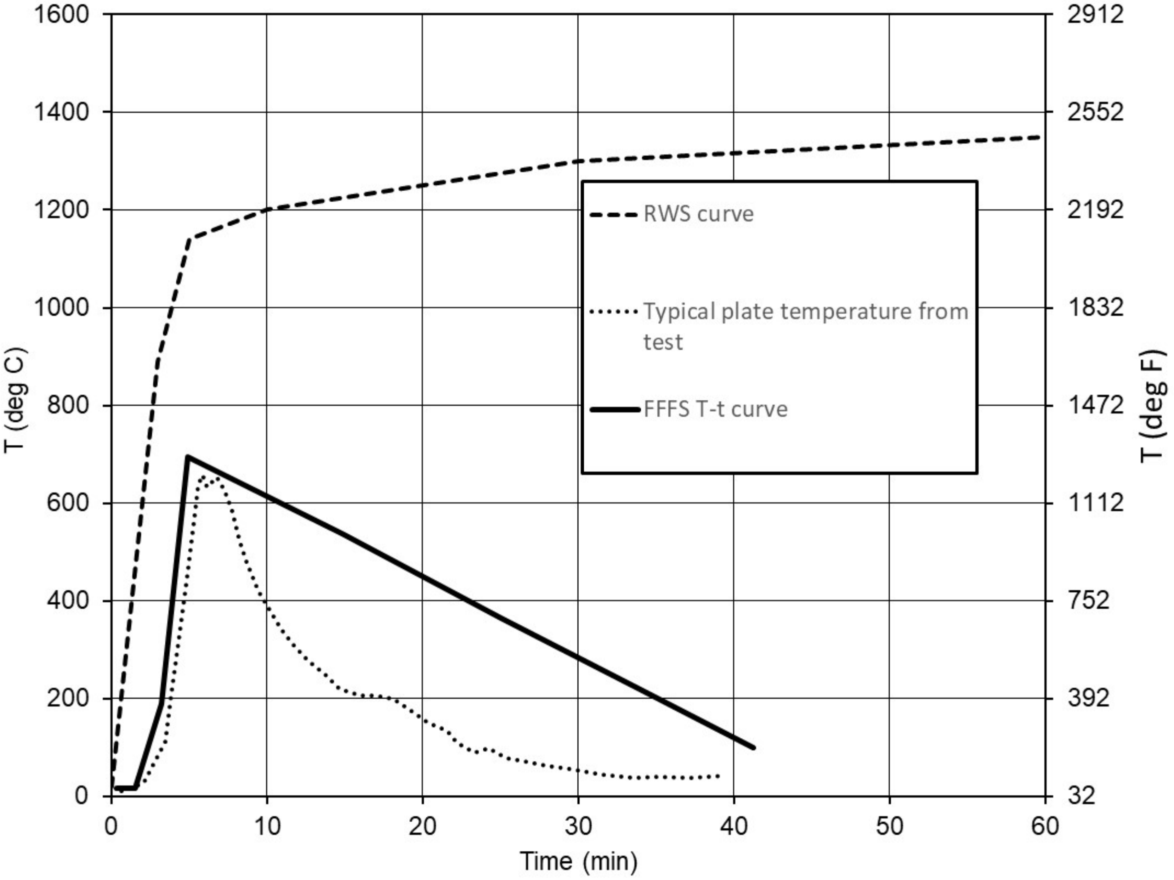


Figure 6-5: Graph. FFFS time-temperature curve [153].

6.3.5 Structural Analysis

Having established a time-temperature curve, the next step is to determine temperatures within the tunnel structure. Key to this analysis are the boundary conditions used and the form of the time-temperature curve. If using the AST, then the heat transfer model should include a boundary condition that factors in the convection and radiation boundary conditions [157] (see Figure 6-6). The shape of the tunnel structure will determine whether the analysis is one-dimensional or multi-dimensional. For smooth slab type ceilings, heat transfer may be considered one-dimensional and can be performed using a one-dimensional semi-infinite slab approach. For more complex geometries, where heat transfer is multi-dimensional, a finite element analysis may need to be employed.

$$q''_{tot} = \epsilon_s \sigma \left(T_{AST}^4 - T_S^4 \right) + h_c \left(T_{AST} - T_S \right)$$

Figure 6-6: Equation. Heat transfer boundary condition [157].

In Figure 6-6 symbols are defined as follows: q''_{tot} is the heat flux at the surface (W/m^2), ε_s is the surface emissivity, which is typically 0.8 to 0.9, σ is the Stefan-Boltzmann constant (5.669×10^{-8} W/m^2/K^4), T_{AST} is the adiabatic surface temperature (K), T_S is the surface temperature (K), and h_c is the convective heat transfer coefficient, which is typically 25 W/m^2/K.

Relevant material properties input into the heat transfer analysis, such as concrete specific heat capacity and conductive heat transfer coefficient, are temperature dependent. They must be estimated based on the temperature range expected. Several documents provide data for concrete property variation with temperature [30] [158]. The properties are highly dependent on type of aggregate, water content, add-mixes, and how the tests were conducted. They are therefore difficult to predict accurately. A range of typical values may be identified from studies for the appropriate concrete aggregate mixture.

Another key to the structural analysis is consideration of spalling. NFPA 502 requires that tunnel concrete structural elements be designed such that fire-induced spalling, which can lead to progressive structural collapse, be prevented. Concrete spalling can be described as the breaking off of layers or pieces of concrete from the surface of a structural element when exposed to high temperatures [159]. Spalling has several forms including [159]:

- Aggregate spalling: crater formation due to the aggregate type.
- Surface spalling: disc shaped flaking from the concrete surface.
- Corner spalling: violent spalling of corner pieces.
- Explosive spalling: very violent spalling of large pieces of concrete.

Spalling can progress deep into the structure and can threaten structural integrity. The primary mechanism of spalling is the vaporization of water trapped within the concrete. As temperature rises, vapor pressure can increase to levels that stress the concrete beyond the failure point, causing pieces to be ejected. The onset of spalling is therefore highly dependent on the moisture content of the concrete structure.

The behavior of concrete at elevated temperatures has shown that spalling can occur at relatively low temperatures and has been reported to occur with at a temperature in the range of 150°C to 250°C [160]. NFPA 502 requires a surface temperature of the concrete of less than 380°C when passive fire protection is used. While spalling in and of itself may not constitute a great risk for the tunnel concrete structure, the loss of concrete surface exposes underlying reinforcement to elevated temperature much more quickly than would occur through direct heat transfer. The addition of polypropylene fibers (PPF) to concrete add-mixes has been shown to reduce or eliminate concrete spalling. The fibers mitigate spalling in concrete by melting when heated and providing channels within the concrete that allow water vapor to escape before building up dangerous levels of pressure. The PPF mixture used must be in sufficient proportion to offer acceptable performance over the project time-temperature exposure.

There are numerous test programs that have identified acceptable values of PPF mixtures. For example, in the 2004 Bostrom study [161], several types of concrete were infused with PPF in various concentrations and exposed to the RWS curve. PPF mix performance was recorded for each type of concrete and results presented in terms of observed depth of spalling, if any. With no fibers included spalling was observed to a depth of up to 10 inches, but with fibers included the spalling was either greatly reduced (maximum 3 inches) or did not occur. None of the samples with a PPF concentration of 0.094 lbm/ft^3 (1.5 kg/m^3) experienced spalling; the only samples that experienced spalling had a PPF concentration of 0.062 lbm/ft^3 (1.0 kg/m^3). Caution is needed though because spalling can vary with concrete mix and loading – generally a test specific to the project is needed. The results also show the dramatic difference in temperature at reinforcement depth when concrete cover has been lost and when it is intact.

The impact of the FFFS on spalling is an item that has not received much investigation. In most situations, the FFFS will reduce the concrete temperature to levels below critical values for spalling to occur. However, if there is a delay in FFFS activation it is possible that critical temperatures could be reached [153]. The mitigation provided by the FFFS in this situation is uncertain.

Additional information on structural strength reduction can be found in the American Society of Civil Engineers (ASCE) Structural Fire Engineering reference [162] and NCHRP 12-85 [148].

6.4 Summary

Questions raised in the introduction are outlined below, along with comments on the findings of the literature survey and synthesis.

Do FFFS reduce the structural passive fire protection requirements (arising per NFPA 502); if so, by how much, and how does system reliability impact this?

> It is demonstrated that FFFS can reduce the FHRR and hence the temperatures that the structure is exposed to. The degree of cooling will depend on the FFFS parameters as well as the fire source. CFD analysis can be used to characterize the thermal environment and to determine a suitable time-temperature curve for structural design. There is a strong coupling between the thermal environment analysis and the subsequent structural design, and coordination is critical. Passive fire protection requirements can be reduced, but key considerations include the thermal response of the concrete, the risk of structural failure (e.g. failures may be less tolerable if the tunnel is in unstable ground) and FFFS reliability. There is still a potential for spalling even with the use of FFFS; the delayed activation of FFFS allows concrete temperatures to increase, which is then coupled with thermal shock after the application of cooler water. A failure of the FFFS system will also increase the likelihood of spalling.
>
> The subject of FFFS reliability when considering compensations for passive fire protection is an area for further research and development. It is important to understand the consequences of FFFS failure for a structure relying on active fire protection, and the likelihood of FFFS failure. Ultimately, compensation of passive fire protection based on FFFS inclusion requires a consensus on an acceptable level of residual risk.

7 SUMMARY

The main goal of this research is to facilitate the design of the FFFS and EVS in an integrated manner. The introduction identified questions to help focus the review and synthesis, and the responses to those questions are summarized as follows:

1. ***What types of tunnels are constructed and how?***
   The four main tunnel types are circular, rectangular, horseshoe, and oval. They are constructed by boring, blasting, excavating, or by sinking a precast tube.
2. ***What are the principal functional systems?***
   The principal functional systems include EVS, FFFS, CCTV, public address and communications, signage, lighting, standpipe, SCADA, PA, power, and drainage.
3. ***What are the U.S. FLS approaches for highway tunnels?***
   The primary FLS approach for highway tunnels is compliance with NFPA 502 via an engineering analysis showing the FLS goals are met. For longer tunnels, this usually includes an EVS at a minimum.
4. ***Where do FFFS fit into the overall FLS picture for a U.S. highway tunnel?***
   For tunnels complying with NFPA 502, FFFS should be considered as part of the overall FLS design. Historically, FFFS have had limited use in U.S. tunnels, but they are becoming more common in line with international practices.
5. ***How does the tunnel construction affect the FPLS system?***
   The tunnel construction will greatly affect the FPLS systems and their installation. For example, a transverse ventilation system cannot be used unless separate air ducts are part of the tunnel construction. FFFS and other systems are less affected by construction type. However, routing of pipework and other elements requires sufficient clearance above the roadway, space for ancillary equipment must be considered, along with supporting infrastructure to supply/remove water from the FFFS.
6. ***What are the design FHRRs recommended?***
   NFPA 502 states that a representative FHRR for an HGV is 150 MW, and a flammable liquid tanker is 300 MW. These values should be used only as a starting point in determining the design FHRR for a given tunnel. The final determination of the design fire should be made after considering all relevant factors on a case-by-case basis for each tunnel (e.g. tunnel geometry, traffic makeup, facility risk, etc.).
7. ***What is the impact of FFFS on FHRR?***
   The expected impact of FFFS varies with system type, application rate, droplet size, and nozzle type. However, various small and full-scale tests indicate that a reduction in peak FHRR of 50 to 70% is likely (assuming prompt activation of the system and a water application rate of 0.10 to 0.15 gpm/ft^2, 6 to 8 mm/min) [1] [2] [3] [4]. Information on nozzle type and impacts on the FHRR could be better documented and this is an area where further research would be beneficial. Laboratory scale testing has shown that FFFS only reduces the FHRR for liquid fuel spills if an AFFF is added [5].

8. ***How do different types of FFFS and their activation and application rates affect the fire?***
   Droplet diameter varies between deluge and mist systems. Mist systems tend to provide greater temperature reduction, but deluge systems have a greater ability of reaching and cooling the burning surface. Water mist droplets are unable to penetrate the fire plume and reach the seat of the fire. For shielded fires water spray cannot reach the seat of the fire and thus performance is similar between deluge and mist.

   Delayed activation of FFFS limits the reduction in peak FHRR achieved [6]. Typically, a higher water application rate results in a slightly lower peak FHRR [2] [3]. However, for deluge system water application rates of 0.15 gpm/ft^2 (6 mm/min) and greater, the difference in peak FHRR (e.g. between 0.15 gpm/ft^2 and 0.20 gpm/ft^2) is small and unlikely to be of significance for integrated FFFS-EVS designs

9. ***What is the role of laboratory scale testing and full-scale testing?***
   Combustion modeling remains a heavily researched topic, and the full physics of combustion are not completely understood. Generating experimental data in full and small-scale tests allows theories to be tested, CFD models to be calibrated, and other practical insights to be gained about how fires burn in tunnels.

10. ***What is the role of CFD modeling?***
    CFD models are a relatively quick and cost effective means of investigating a particular fire scenario in a tunnel where the FHRR is specified a priori. CFD can be reliably used to predict gas phase cooling. However for FHRR or fire spread prediction, in order to draw any useful conclusions from a model, it must be calibrated against experimental data. CFD also has a limited ability to model certain aspects of FFFS in tunnels (e.g. FFFS interruption of the combustion/pyrolysis process).

11. ***How do water application rate and other design parameters link to NFPA 502 goals?***
    As per Table 4-4, the water application rates (with deluge systems) of 0.30 gpm/ft^2 to 0.15 gpm/ft^2 (12 mm/min to 6 mm/min) could achieve fire control. No water application achieved fire suppression unless the fire was sufficiently exposed such that water application could directly reach the seat of the fire. Recent data suggest water application rates as low as 0.05 gpm/ft^2 (2.2 mm/min) could achieve control. Further study with testing or analysis (CFD) is needed to better quantify threshold limits and system details (nozzle layout, type, water application rate) with respect to NFPA 502 goals.

12. ***What level of effort is needed for maintenance and inspection of FFFS?***
    Regular maintenance and inspection of FFFS are critical to their effective operation. On average, FFFS have a high effectiveness value [7]. Maintenance requirements for FFFS are outlined in NFPA 25 [8]. Many valve components need weekly or monthly inspections; however, the sprinkler piping and nozzles only need annual inspections. Based on data from thousands of fire events, the reliability rate of a properly designed, maintained, and operated FFFS is 99.4% [9].

13. ***What is the deflection of water droplets by the EVS?***
    Generally, not a concern, if multiple zones can be activated, refer to Section 5.3.7. A validated modeling methodology for water spray drift would be useful.

14. ***Is there a critical velocity equation that is applied when the FFFS are applied?***
One equation has been derived, based on test data, refer to Section 5.3.2. Figure 5-19 provides a correlation but the FHRR is limited to a maximum of 40 MW. For FHRRs greater than 40 MW, there is no specific equation for critical velocity with FFFS applied, and it is necessary to use CFD modeling or testing.

15. Where are the vulnerable points in an integrated FFFS-EVS design?
Research needs due to vulnerability include:

- Develop a more general equation for critical velocity with ventilation and FFFS using CFD modeling.
- Pressure loss caused by the FFFS components and FFFS spray (droplets and humidity) – investigate with testing and analytical sums
- Pressure loss caused by the fire when an FFFS is operating.
- FFFS impact on FHRR – agree on a nozzle type and water application rate for a certain FHRR outcome.
- In terms of tenability for occupant egress, further information would be useful as follows:
    - Additional data on HGV toxic gas yields.
    - Measurement of irritant species for a fire with and without FFFS.
    - Timing for egress, FFFS activation, fire growth, etc.

16. Do FFFS reduce the structural passive fire protection requirements *(arising per NFPA 502)*; if so, by how much, and how does system reliability impact this?
It is demonstrated that FFFS can reduce the FHRR and hence the temperatures that the structure is exposed to. The degree of cooling will depend on the FFFS parameters as well as the fire source. CFD analysis can be used to characterize the thermal environment and to determine a suitable time-temperature curve for structural design. There is a strong coupling between the thermal environment analysis and the subsequent structural design, and coordination is critical. Passive fire protection requirements can be reduced, but key considerations include the thermal response of the concrete, the risk of structural failure (e.g. failures may be less tolerable if the tunnel is in unstable ground) and FFFS reliability. There is still a potential for spalling even with the use of FFFS; the delayed activation of FFFS allows concrete temperatures to increase, which is then coupled with thermal shock after the application of cooler water. A failure of the FFFS system will also increase the likelihood of spalling.

The subject of FFFS reliability when considering compensations for passive fire protection is an area for further research and development. It is important to understand the consequences of FFFS failure for a structure relying on active fire protection, and the likelihood of FFFS failure. Ultimately, compensation of passive fire protection based on FFFS inclusion requires a consensus on an acceptable level of residual risk.

Relevant to the basic goal of this research, the following key areas are identified for further investigation as part of the computer modeling and testing (laboratory and full-scale) efforts:

- Critical velocity:
  - Critical velocity is of interest because the ability to predict critical velocity when an FFFS is operated is the most fundamental input to an integrated EVS design. Existing equations have limited validity at high FHRRs. The goal for further investigation is to develop a validated and verified method of modeling tunnel fires to determine critical velocity with FFFS, and to extend the range of validity of existing equations.
- Transverse ventilation:
  - Transverse ventilation is of interest because many existing tunnels in the U.S. use a transverse ventilation system. Of concern is how smoke management in a transverse scheme is affected by the FFFS, as well as whether FFFS droplets can become entrained in the exhaust airflow and lower the effectiveness of the FFFS. The laboratory testing and full-scale testing, which is planned to follow the computer modeling, will be focused to provide specific test data for validation of models and equations.

Most new tunnels in the U.S. are using a longitudinal EVS via the action of jet fans. The literature survey and synthesis described a design approach where a one-dimensional calculation is used to compute the fan thrust requirements. As part of that review several key parts of the calculation where the FFFS have an impact were identified. The summary below notes where further measurements are proposed as part of this research effort and the contributions that are anticipated.

- Fire heat release rate (Section 5.3.1):
  - The impact of FFFS on the FHRR is well-established from full-scale tests. Measurements of FHRR (laboratory and full-scale) will provide useful additional data to further confirm the efficacy of the FFFS for a given water application rate and nozzle layout/type.
- FFFS cooling of the combustion products (Section 5.3.3):
  - The ability of the FFFS to cool combustion products is well-established. Critical velocity research, modeling and testing (measurement of temperatures), will provide additional data to further the knowledge in this area.
- Pressure loss (airflow resistance) due to fire (Section 5.3.4):
  - Equations have been developed for pressure loss due to fire. Measurements of static pressure (laboratory and full-scale) upstream and downstream of the fire will provide useful additional data to further confirm validity of the equations and to understand the FFFS impacts.
- Pressure loss (airflow resistance) due to the FFFS (droplets and humidity) (Section 5.3.5):
  - Measurements of pressure loss and humidity in the full-scale and laboratory scale tests will provide useful data for validation of analytical calculations. Cold flow measurements will provide useful data related to droplet drag.

- Friction losses introduced by FFFS pipework (Section 5.3.6):
  - Measurements of pressures in the full-scale and laboratory scale tests with ventilation operating will provide useful data for validation of friction to due FFS pipework.
- Water droplet deflection due to the EVS (Section 5.3.7):
  - Cold flow measurements will provide useful data related to droplet drift (visualization) due to ventilation. Computer modeling for droplet drift will provide useful data for validation of a model to investigate transverse ventilation and droplet entrainment.
- Tenability for egress and fire fighting (Section 5.3.8):
  - The impact of the FFFS on generation of carbon monoxide is such that the yield of CO is increased due to incomplete combustion. Measurement of CO will provide useful data to help further verify this result. Measurement of irritant gas concentrations, although not a primary focus of this work, would provide useful additional data for future computer model development.

Additional topics that merit further investigation include:

- Impact of external wind on conditions inside the tunnel and contribution to fire growth rate or impact on FFFS performance.
- Further work to understand spalling and predict spalling, thus allowing an analysis to consider spalling potential following a delay in the FFFS operation.
- Further work to look at whether there are any interactions between spalling and FFFS operation.
- Review and synthesis on dangerous goods and interaction with FFFS

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