

RECOMMENDED AASHTO GUIDELINES FOR EMERGENCY VENTILATION SMOKE CONTROL IN ROADWAY TUNNELS

Prepared for:

AASHTO Standing Committee on Highways

Prepared by:

Dr. Igor Maevski, PE
Jacobs Engineering
Two Penn Plaza, Suite 0603
New York, NY 10121

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NCHRP PROJECT 20-07/TASK 363

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TABLE OF CONTENTS

EXECUTIVE SUMMARY	7
1 INTRODUCTION	9
1.1 Roadway Tunnels Emergency Ventilation – Current Industry Knowledge and Practice.....	9
1.2 Applicable Regulatory Standards and Guidelines	11
1.2.1 U.S. Standards, Synthesis Studies and Guidelines	11
1.2.2 International Standards and Guidelines	13
1.2.3 Other publications for Emergency Ventilation Smoke Control in Roadway Tunnels	24
2 ROAD TUNNEL FIRES	28
2.1 Main Design Fire Parameters	28
2.2 Impact of Fire Size on Smoke Management Requirements	33
3 TUNNEL EMERGENCY VENTILATION AND SMOKE CONTROL DESIGN GUIDELINES	40
3.1 Types of Road Tunnel Ventilation Systems	41
3.2 Tunnel Ventilation Systems Conditions for Application and Configurations	57
3.2.1 Tunnel length, geometry and grades.....	58
3.2.2 Traffic conditions	61
3.3 Tunnel Ventilation Fans Utilization and Placement	64
3.4 Effects of Ventilation on Tunnel Fires and Fire Sizes.....	71
3.5 Fire Smoke Stratification and Length of Stratification and its Impact on Emergency Ventilation ..	72
4 TUNNEL FIRE DETECTION AND VENTILATION IMPACT	77
5 TUNNEL FIXED FIREFIGHTING SYSTEMS AND VENTILATION IMPACT	78
5.1 Interaction Between Water Based Fixed Fire Suppression and Tunnel Ventilation Systems.....	80
5.2 Interaction Between Firefighting Operation and Tunnel Ventilation Systems	86
6 TUNNEL EMERGENCY VENTILATION CONTROLS	90
7 REFERENCES	95
8 GLOSSARY	100
APPENDIX A: TUNNEL FIRE DETECTION AND WARNING SYSTEMS	102
APPENDIX B: TUNNEL FIXED FIREFIGHTING SYSTEMS	107
Applicability of Tunnel Fire Suppression Systems	108

TABLE OF FIGURES AND TABLES

Figure 1.1: A roadmap for key decisions to design tunnel ventilation and fixed firefighting systems.....	10
Figure 1.2. Schematic representation of the integrated approach to safety	14
Figure 1.3 Integrated safety circle for tunnels	15
Figure 1.4 Holistic approach to risk analysis	16
Figure 1.5 Example of system-based approach to risk analysis.....	17
Figure 1.6 Flowchart of the procedure for risk assessment.....	19
Figure 1.7 Tunnel safety concept.	20
Figure 2.1: Sample decision making chart on design fire parameters.....	32
Figure 2.2 Diesel fuel pan fire of 5 MW in I-90 tunnel in Seattle (left); Winnipeg Transit Bus on Fire (right)	34
Figure 2.3 Sketch with three stratification regions.....	35
Figure 2.4: Smoke flow rate versus fire heat release rate	36
Figure 3.1: Mean wind pressure coefficients	44
Figure 3.2: Configurations of tunnel portals tested by Blendermann	45
Figure 3.3: Example of design process for consideration of longitudinal ventilation for the road tunnel ventilation system selection.....	48
Figure 3.4: Diagram of longitudinal ventilation controlling smoke and hot gases	48
Figure 3.5 Velocity vectors and pressure for jet fans installed close to the portal and blowing out of the portal	50
Figure 3.6 Tunnel flow rate as a function of center of jet fan distance from the exit portal (example)	51
Figure 3.7: Saccardo nozzle ventilation.....	52
Figure 3.8: Longitudinal ventilation system with shafts utilizing the Coanda effect	53
Figure 3.9: Tunnel with a single point extraction system.....	56
Figure 3.10: Roadway Grade Factor	58
Figure 3.11: Tunnel Categories. Extracted from NFPA 502 (2014 edition)	62
Figure 3.12: Typical jet fan arrangement in niche (ASHRAE Applications Handbook).....	65
Figure 3.13: Typical jet fan installations in road tunnels	66
Figure 3.14: Longitudinal ventilation with Saccardo nozzle	69
Figure 3.15: Schematic of backlayering of smoke in a tunnel fire	73
Figure 3.16: Point extraction ventilation	74
Figure 5.1: Effects of water based fixed firefighting systems.....	78
Figure 5.2: Displacement of FFFS water particles as the result of longitudinal air velocity	82
Figure 5.3: Longitudinal ventilation with fixed fire suppression system	83
Figure 5.4: Photographs of a fire test	84
Figure 5.5: Single point extractions with fixed fire suppression system.....	85
Figure 5.6: Fire and rescue operation dealing with a car fire in a twin-bore tunnel with queuing traffic.....	87

Figure 5.7: Fire and rescue operation dealing with a car fire in a single-bore tunnel	88
Figure 5.8: Firefighting timeline	89
Figure 6.1: Overview of the tunnel ventilation control loop	91
Figure 6.2: Fire detection and validation process flow chart.....	92
Figure 6.3: Example of project established time-of-tenability curve	93
Figure B.1: Schematic effect of suppression on Heat Release Rate. Courtesy of Arnold Dix	109
Figure B.2: NFPA 13, NFPA 15, and other International Water Application Rates.....	111
Figure B.3 HRR for HGV Fire with and without fire suppression and with delay 8 min activation of FFSS (test 6).	112
Figure B.4: Fire Heat Release Rate for Varying Water Application Rates-Unshielded Fires.....	113
Table 2.1: Design fire variables [3].....	30
Table 2.2: Smoke, CO ₂ and CO production [17].....	37
Table 2.3: Simplified example of tunnel fire safety risk and fire life safety system needs based on the tunnel length and traffic conditions	38
Table 3.1: Configuration of tunnel portals tested by W. Blendermann [36].....	43
Table 3.2: Longitudinal ventilation operation in tunnels with one-way and two-way traffic	63
Table 3.3: Transverse ventilation system smoke control strategies [15]	64
Table 3.4: Maximum air temperatures experienced at ventilation fans during Memorial Tunnel Fire Ventilation Test Program [11]	67
Table 3.5: Distances over which jet fans are assumed to be destroyed by a tunnel fire (BD 78/99) [43]	68
Table 3.6: Smoke temperatures near the ceiling, with airflow close to critical velocity (CETU, 2003) [43].....	68
Table 3.7: Influence of ventilation rate on fire growth rate [45].....	72
Table 5.1: Impact of fixed fire suppression system on tunnel fire safety	79
Table 5.2: Expectations from tunnel ventilation and fixed fire suppression systems	80
Table 5.3: Analysis of fixed fire suppression system impacts on performance of single point extraction ventilation.....	86
Table B.1: Large Scale Fire Tests Schedule [48].....	112
Table B.2: Comparison of water mist and deluge systems components	115

EXECUTIVE SUMMARY

The document provides guidance to the owners and agencies, law enforcement agencies, first responders, designers, and vendors in reference to emergency tunnel ventilation. It can also be used by State Departments of Transportation (DOTs) for implementing best practices within their tunnel operation program in order to improve public and emergency responder safety. The tunnel ventilation system is the main tunnel fire life safety system. An objective of the tunnel ventilation system is to control and/or extract smoke and heated gases and to provide a non-contaminated environment for egress of tunnel users. Another objective is to support firefighting and rescue operations. In both cases, the primary goal is to control smoke and hot gases as the result of fire. Choosing the type of ventilation system is one of the most important decisions when designing a tunnel. While every situation has its unique features, some general conclusions are drawn about the relative usefulness and efficiency of the various types of ventilation systems for smoke control.

Memorial Tunnel fire tests sponsored by FHWA, ASHRAE and others concluded that full transverse and semi-transverse ventilation systems used in many old US tunnels designed to the old standards and installed over 40 years ago, were ineffective in the management of heat and smoke for fires of 20 MW (bus fire) or larger. To manage large fires, the old systems may need to be modified.

Nowadays, there are two commonly used concepts for smoke management in road tunnels to achieve a smoke-free environment for egress:

- Longitudinal ventilation concept - directing smoke along the tunnel in the opposite direction of egress by completely pushing the smoke to one side of the fire (preferably applied to non-congested unidirectional tunnels where there are normally no people downstream of the fire and is typically achieved by longitudinal ventilation). It introduces air into or removes smoke and gases from the tunnel at a limited number of points, primarily by creating longitudinal airflow through the length of the tunnel, from one portal to the other. Longitudinal ventilation can be accomplished either by injection, central fans, jet fans mounted within the tunnel, nozzles (often installed at the portals and called a Saccardo system), or through a combination of injection and extraction at intermediate points. The system must generate sufficient longitudinal air velocity called “critical velocity” to prevent backlayering of smoke.
- Extraction ventilation concept - extracting smoke at the fire location by keeping the smoke stratification intact, leaving more or less clean and breathable air suitable for evacuation underneath the smoke layer to both sides of the fire (applicable to bi-directional or congested unidirectional tunnels and is typically achieved by zoned transverse ventilation or single point extraction). Extraction ventilation concept typically requires exhaust ventilation ducts and a system capable of localizing hot gases and smoke and extracting them at the fire location using exhaust high temperature rated ventilation fans.

The document provides a roadmap for selecting a tunnel ventilation system and types of tunnel ventilation fans. Fixed firefighting system, where provided, shall be coordinated with ventilation. Tunnel ventilation system response shall be coordinated with fixed firefighting system response and properly documented in the emergency response plan. Fixed firefighting systems cannot replace the tunnel ventilation system; however it could reduce the fire size, fire growth and ventilation requirements.

Every tunnel should have a comprehensive emergency response plan and concept of tunnel operation documents. These documents should address specific instructions to the tunnel operators on how to operate the tunnel ventilation system during fires inside and in the vicinity of the tunnel and other possible scenarios considering the unique nature of the tunnel. The strategies may differ depending on the type of ventilation system, traffic conditions, presence of other fire life safety systems such as fixed firefighting systems, and phase of fire emergency (evacuation or firefighting phase). The control system should allow for the response of the ventilation system to a reported incident in accordance with emergency response plan. This response is based on information retrieved from various sources inside and outside the tunnel. The information is analyzed and validated and the ventilation response could be activated automatically, semi-automatically, or manually. Consideration needs to be given to the complexity of the ventilation system, other tunnel fire life safety systems and the organization of the operating personnel. A complex ventilation system is much more efficiently managed by an automatic or semi-automatic system than by an operator performing under high stress conditions. The ventilation control should ensure adequate response for all conceivable fire scenarios including scenarios where some equipment or sensors fail to respond. Control methods must take into account that the conditions may change over time. Different tunnels may require different control approaches.

The general recommendations to the operators applicable to all fire situations are:

- Respond in a timely manner to save lives;
- Activate fire life safety systems, such as tunnel ventilation, in accordance with the emergency response plan;
- Do not blow smoke in the direction of evacuees. Direct fresh air to support evacuation;
- Do not change the selected ventilation mode without direction from incident commander, especially during the evacuation phase. Changing ventilation mode, such as reversing fans or airflow during a fire event, could spread smoke throughout the tunnel;
- Over-ventilating may increase the fire size and fire growth rate and may destroy smoke stratification;
- Periodic training of tunnel operators, first responders, and their interactions is essential for a successful response. Training simulators are useful tools for ventilation controls training.

The document evaluates the fire safety risks for different type of tunnels depending on tunnel length and usage and provides general mitigation means and strategies for each general case.

As far as fire and rescue services are concerned, the most important measures that can reduce the severity of accidents are:

- Short distances to, and simple means of reaching escape routes for those escaping from a fire and rescue work;
- Fire fighters can approach the fire as safely as possible (in protected environment) and safely escape as needed;
- Fire cannot grow excessively before firefighting work can start.

These various conditions can be achieved in different ways, but there must be an overall safety program that identifies all the parameters involved, ensures that they work together, and creates the best conditions for a high level of safety.

1 INTRODUCTION

The objective of this document is to improve the safety of highway tunnels by developing methods and guidelines for emergency tunnel ventilation. The document provides guidance to the owners and agencies, law enforcement agencies, first responders, designers, and vendors in reference to emergency tunnel ventilation. It can also be used by State Departments of Transportation (DOTs) for implementing best practices within their tunnel operation program in order to improve public and emergency responder safety. To date, there is limited experience and knowledge regarding effective practices for ventilating a significant roadway tunnel fire. This guideline focuses on developing improved practices for road tunnel fire emergency ventilation which include but are not limited to, full transverse, partial transverse, and longitudinal type ventilation systems. The guideline considers tunnel geometrics such as tunnel altitude, physical dimensions (i.e. length, cross section), type of traffic flow (i.e. single or bi-directional flow), and fan utilization and placement. It also considers cargo types and quantities as they pertain to fire heat release rates (FHRRs) and ventilation requirements. The guideline determines the effects of ventilation on tunnel fires including fire size. It explores the interaction of firefighting and ventilation system operation. The document addresses the practicality of emergency tunnel ventilation system control and its application when other systems, such as fixed firefighting systems, are used.

This work is part of a larger effort to develop best practices that aim to lead to future development of tunnel design/construction specifications and operations.

Guidelines concerning construction are not included in the scope of this document. These guidelines also do not apply to the following facilities:

1. Rail tunnels
2. Mass transit tunnels and stations
3. Parking garages
4. Bus terminals
5. Truck terminals
6. Any other facility in which motor vehicles travel or are parked

1.1 ROADWAY TUNNELS EMERGENCY VENTILATION – CURRENT INDUSTRY KNOWLEDGE AND PRACTICE

There is currently no in depth guideline for emergency ventilation in roadway tunnels in the U.S. The National Fire Protection Association (NFPA) produces a document, NFPA 502, that provides general requirements with further clarifications in its annex materials [1].

These guidelines are intended to utilize current industry knowledge to provide guiding principles for emergency ventilation with references to NFPA 502 and other standards. They are not intended to replace or supersede the NFPA 502 Standard. In case of any conflicts noted between the guidelines and current or future editions of NFPA 502, the NFPA document takes precedence.

One of the intents of this guideline is to help state highway officials understand the risks present in and key decisions needed to design tunnel ventilation and fixed firefighting systems. While the process is quite complicated, the guidelines make an attempt to simplify the process to the roadmap in Figure 1.1 as follows:

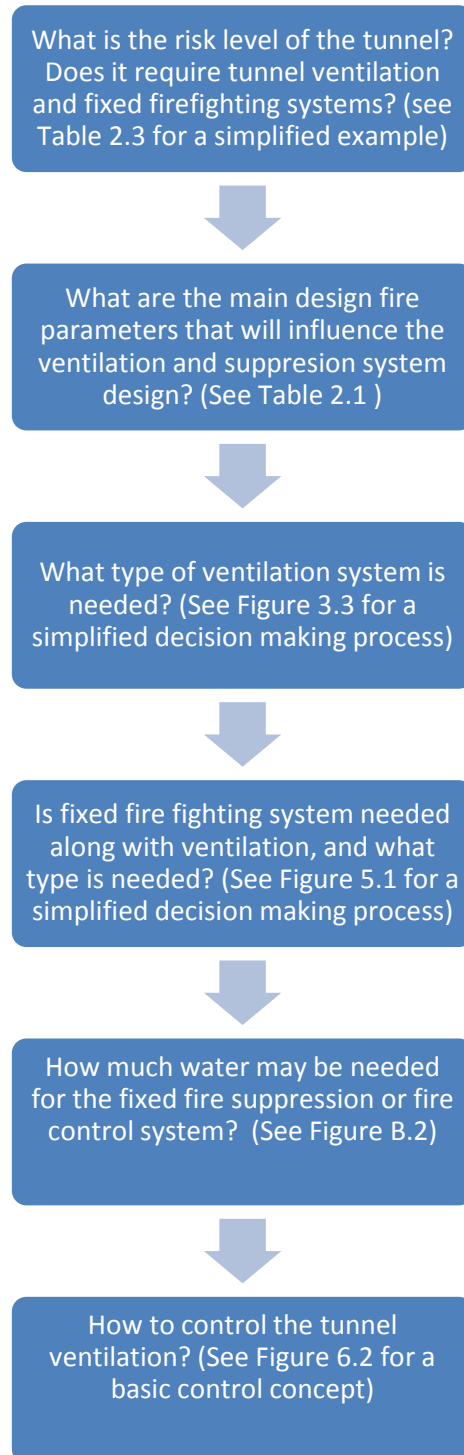


Figure 1.1: A roadmap for key decisions to design tunnel ventilation and fixed firefighting systems.

1.2 APPLICABLE REGULATORY STANDARDS AND GUIDELINES

1.2.1 U.S. Standards, Synthesis Studies and Guidelines

NFPA 502, Standards for Road Tunnels, Bridges and Other Limited Access Highways (2014) is the most referenced fire and life safety document for U.S. road tunnels [1]. The document defines fire and life safety requirements, including emergency ventilation for road tunnels. This standard covers limited access highways, bridges, road tunnels, and roadways beneath air-right structures and sets design requirements wherever applicable for the fire and life safety systems, structures, and emergency response procedures. This standard is updated every three years based on the most up to date information on tunnel fires, technological developments, and the experience of tunnel owners, agencies, law enforcement agencies, first responders, designers, and vendors. This document consists of the main standard and annex materials. The standard (main) part sets requirements for emergency ventilation and other fire and life safety systems. The annex of this document clarifies requirements set in the main part. Annex I, titled “Tunnel Ventilation System Concepts,” discusses types of road tunnel ventilation systems and Annex J, titled “Control of Road Tunnel Emergency Ventilation System,” discusses ventilation operational modes and controls requirements. Also, Annex A, titled “Explanatory Material,” provides a table of the relationship between vehicle types and heat release from a resulting fire. Most U.S. agencies and many international agencies rely on NFPA 502 for tunnel safety design.

NCHRP Synthesis 415, Design Fires in Road Tunnels (2011) [3]. This document, produced by the National Cooperative Highway Research Program (NCHRP), which is administered by the Transportation Research Board (TRB), is a synthesis study of best national and international practices for fire and life safety and road tunnel emergency ventilation system design. It contains references to standards and guidelines developed around the world. The study discusses design fire scenarios in tunnels, full and small scale fire tests, modeling of the tunnel fires, main design fire parameters, and tenable environment conditions, while also providing a compilation of international tunnel ventilation standard requirements. This document includes a survey of national and international tunnel owners and agencies on road tunnel fires and best practices of tunnel fire management including fire frequency; consequences of fire incidents; severity of tunnel fires; existing practice of fire management; best design practice; maintenance, repair and rehabilitation of fire management systems; and a discussion on computer based training tools for operators to manage fire. In Chapter 9, it discusses the relationship between vehicle types, heat release, and ventilation requirements. In Chapter 13, the study discusses the effects of ventilation on tunnel fires and fire size as well as fixed fire suppression systems and their impact on design fire size. The annex to the synthesis provides a comparison of national and international standard requirements and additional information on past tunnel fires and fire tests.

NCHRP Report 525, Volume 12, Making Transportation Tunnels Safe and Secure (2006) [4]. While this document mostly addresses tunnel security issues, it provides numerous references to tunnel ventilation and control systems. This document provides a study about tunnel fire cases, potential hazards, countermeasures, and emergency system operation. The International Technology Scanning Program sponsored by the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) issued a report in 2006 titled, “Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response,” with the objective of discovering what is being done internationally for underground transportation systems regarding safety, operations, and emergency response. This research project aimed to provide safety and security guidelines for transportation tunnel owners and operators. To accomplish this task, a

team of experienced design engineers, builders, and operations personnel collaborated with safety and security experts to address the following questions:

- What natural hazards and intentional threats do they face?
- How would they be introduced?
- What are the vulnerable areas of their tunnel?
- How much of a disturbance would there be?
- How can they avoid these hazards and threats?
- How can they prepare themselves for this disturbance if it occurs?

The report provides guidelines for protecting tunnels by minimizing the damage potential from extreme events so that they may be returned to full functionality in a relatively short period of time following damage. This report examines safety and security guidelines in identifying principal vulnerabilities of tunnels to various hazards and threats. It also explores potential physical countermeasures, potential operational countermeasures, and deployable integrated systems for emergency-related command, control, communications, and information.

The report is organized in seven chapters and includes:

- Hazard and Threats Analysis
- Case Studies on Fire Events in Road and Railway Tunnels in Different Countries
- Tunnel Structural and Vulnerabilities Analysis
- Countermeasures and System Integration

TRB Report 883, Tunnel Ventilation, Lighting, and Operation (1982) [5]. This report is the only document on tunnel ventilation developed by the TRB. It was developed by a group of engineers from Ministère des Transports du Québec, TLT-Babcock, Sverdrup & Parcel (Jacobs Engineering) and Fenco Consultants. This document includes best tunnel ventilation design practice and tunnel fan design issues. However, it does not address emergency ventilation and smoke control issues.

NCHRP Report APTD-0684, Basis for Establishing Guides for Short-Term Exposure of the Public to Air Pollutants (1971) [6]. This report contains an evaluation of the relationship between exposure to a pollutant and its effect on the population. The report discusses the selection of short-term public air pollution exposure limits. Information presented in this report is outdated.

NCHRP 20-07/Task 230: Safety and Security in Roadway Tunnels [7]. Prepared by Kathleen Almand from the Fire Protection Research Foundation in 2008, this report is a collection of papers and documents from the workshop held on November 29 and 30, 2007 at the National Academies Beckman Center in Irvine, CA. The NCHRP project panel selected five international speakers to address the key research areas identified in the AASHTO Domestic Scan Program – Standing Committee on Highways. Three additional domestic speakers were invited to address the scan program, NCHRP Report 525 / TCRP Report 86, Vol. 12 [4]: Making Transportation Tunnels Safe and Secure, and a review of worldwide standards for fire safety in roadway tunnels. Participants developed the ideas for new research projects needed on Safety and Security in Road Tunnels.

FHWA Reports No. FHWA-RD-78-184; 185; 186; 187 - Aerodynamics and Air Quality Management of Highway Tunnels [8]. These reports were published in 1979 and provide the basic principles and methods of tunnel

aerodynamics calculations, vehicle emissions calculations, and ventilation controls. It presents concepts and detailed knowledge of the tunnel ventilation simulation software TUNVEN.

FHWA Technical Manual for Design and Construction of Road Tunnels – Civil Elements FHWA -NHI-10-034 [9].

This comprehensive document provides general guidelines and recommendations for planning, designing, the construction of, structural rehabilitation, and repairing of civil elements for road tunnels including a brief coverage of fire safety and ventilation.

FHWA Prevention and Control of Highway Tunnel Fires 1998 [10]. This guideline presents methods of preventing, responding to, and controlling fires in existing and future highway tunnels.

ASHRAE Handbook of HVAC Applications, Chapter 15 – Enclosed Vehicular Facilities (2015) [11]. This document summarizes international and national knowledge on tunnel ventilation and addresses ventilation under normal and fire emergency conditions. It is prepared by a group of experts in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and is updated every four years.

Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual. July 2015. Publication No. FHWA-HIF-15-005 [12]. This manual provides guidelines on tunnel operations, maintenance, inspection, and evaluation that help ensure tunnels remain in safe condition and continue to provide reliable levels of service. To help safeguard tunnels and ensure reliable levels of service on public roads, the FHWA developed the National Tunnel Inspection Standards (NTIS), the Tunnel Operations Maintenance Inspection and Evaluation (TOMIE) Manual, and the Specifications for National Tunnel Inventory (SNTI). The NTIS contains the regulatory requirements for the tunnel inventory and inspection program; the TOMIE Manual and the SNTI have been incorporated into the NTIS to expand upon these requirements. The TOMIE provides uniform and consistent guidance on the operation, maintenance, inspection, and evaluation of tunnels.

1.2.2 International Standards and Guidelines

The NFPA 502 Standard is developed with the support of the tunnel engineering community around the world by synthesizing the best international practices. The most known international organization that sets requirements for emergency road tunnel ventilation is the World Road Association (PIARC), which has working groups representing the international practice. In addition, there are standards and guidelines developed by the European Union (EU), Australia and many other countries that have numerous road tunnels and have over a century of experience in road tunnel ventilation systems. The EU defines only the minimum standard in a very general way. Various European countries, such as Switzerland, Austria, Germany, and Norway have their own standards which provide guidelines for tunnel ventilation operation. For example, in Switzerland the Federal Roads Office (FEDRO / ASTRA) is responsible for national roads and specifies safety requirements that comply with EU-directive 2004/54/EC. A series of national guidelines specify higher requirements than those in the EU-directive. They clearly identify when a risk analysis has to be carried out when there are differences between the national standards and the guidelines. Most of the risk analysis models require computational fluid dynamics (CFD) analysis for ventilation and egress modeling to be performed.

PIARC has established several working groups to address tunnel safety, fire, and ventilation issues. Representatives from many countries around the world are participants of those working groups and have developed a number of international documents:

- PIARC Integrated Approach to Road Tunnel Safety 2007 [13]. This report was prepared by Working Group 2 'Management of tunnel safety' of the Technical Committee C3.3 on Road Tunnel Operation of the World Road Association PIARC. This report proposes an integrated approach to road tunnel safety, which has been developed in co-operation with the European research projects SafeT and UPTUN. The report summarizes general principles and current perspectives on road tunnel safety and includes practical tunnel project experience. The key elements for an integrated approach to road tunnel safety are:
 - Safety level criteria (regulations and recommendations);
 - Infrastructure and operational measures for tunnel safety;
 - Socio-economic and cost-benefit criteria;
 - Safety assessment techniques (safety analysis and safety evaluation);
 - Road tunnel usage;
 - Stage of the tunnel life (planning, design, construction; commissioning; operation, refurbishment or upgrading);
 - Operating experience;
 - and tunnel system condition.

A schematic representation of the integrated approach to the safety of new and in-service tunnels is shown in Figure 1.2:

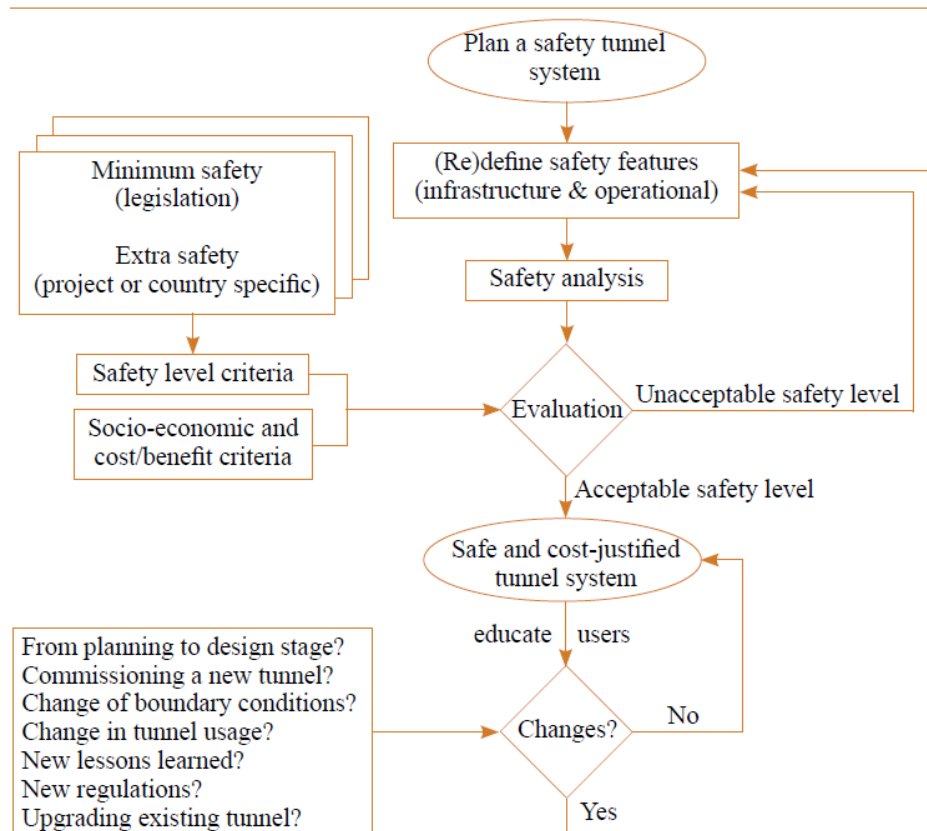


Figure 1.2. Schematic representation of the integrated approach to safety [13]

Integrated safety for tunnels can be presented as a 'safety circle' (see Figure 1.3). It can be inefficient to focus on improving the safety performance of only one element in the sequence without considering the safety performance of the other elements.

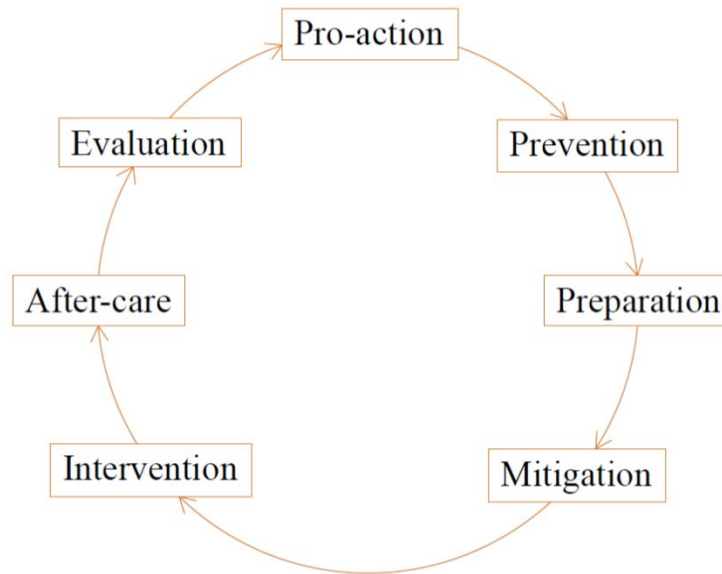


Figure 1.3 Integrated safety circle for tunnels [13]

- PIARC Fire and Smoke Control in Road Tunnels - 05.05.B. (1999) [14]. This book provides general guidelines and functional requirements for fire and smoke control in road tunnels. Recently PIARC issued the report “Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations” 2016.
- PIARC Risk Analysis for Road Tunnels. R02. 2008 [2]. This report has been prepared by Working Group 2 “Management of Road Tunnel Safety” of the Technical Committee C3.3 Road Tunnel Operation of the World Road Association PIARC. Risk analysis is an important tool which can be used to help improve and optimize the safety of road tunnels. Although the likelihood of major tunnel incidents is low, the consequences can be severe in terms of casualties, damage to tunnel structures and equipment, and the impact on the transport economy. For example, the fire in the Mont Blanc tunnel in 1999 claimed 39 lives, led to its closure for 3 years, and incurred economic losses of about 300 million euros. Risk analysis is now explicitly required by the European Directive 2004/54/EC in the minimum safety requirements for road tunnels in the Trans-European Road Network. Risk analysis involves the identification of hazards and the estimation of the probability and consequences of each hazard. The risks are determined from the product of their probability and consequences. Once analyzed, the risks need to be evaluated and, if unacceptable, need to be treated (risk mitigation by additional safety measures). A wide range of qualitative and quantitative methods are available. The report presents two families of suitable approaches for the risk assessment of road tunnels:
 - A scenario-based approach, which analyses a defined set of relevant scenarios in terms of frequency and/or consequences; the risk assessment is done separately for each individual scenario.
 - A system-based approach, which investigates an overall system in an integrated process, including all relevant scenarios influencing the risk of the tunnel, thus obtaining risk values for the whole system.

For the purpose of risk evaluation, the procedure to determine whether the tolerable risk has been achieved, several different types of risk criteria are available. These criteria include expert judgement, scenario related criteria (e.g. threshold values for scenario probabilities or escape time to a point of safety), individual risk (e.g. probability of death per year for a specific person exposed to a risk) and societal risk (e.g. expected number of fatalities in the tunnel per year or a frequency-number of fatalities [FN] curve). The choice of which criteria to apply depends on the application. Quantitative risk criteria can be adopted as absolute threshold values (e.g. a system is safe if the relevant risk value of the system is lower than the defined threshold value) or for relative comparisons (e.g. comparison of different safety measures or comparison of a system to a “safe” reference system).

The meaning of risk analysis and its characteristics can be summarized as follows:

- risk analysis is a systematic approach to analyze sequences and interrelations in potential incidents or accidents, hereby identifying weak points in the system and recognizing possible improvement measures, such as ventilation improvements;
- the term “Risk Analysis” covers a large family of different approaches, methods and complex models combining various methods for specific tasks;
- risk analysis can include a quantification of risks which can be used as the basis of a performance-based approach to safety;
- a general basic principle of all kinds of risk analysis for road tunnels should be a holistic approach including infrastructure, vehicles, operation and - last but not least – users (see Figure 1.4).

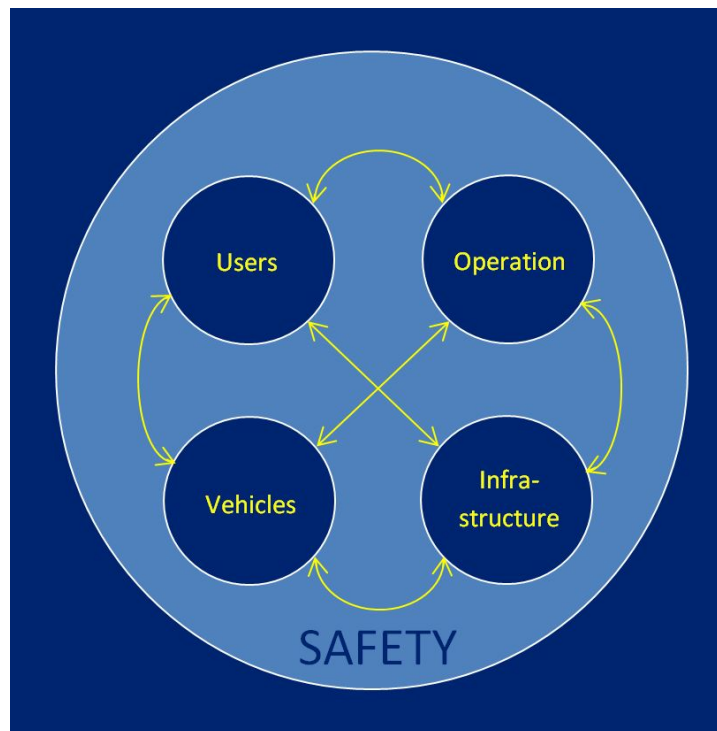


Figure 1.4 Holistic approach to risk analysis [2]

All the methods exhibit specific advantages and disadvantages, but none can claim to be the most suitable in practical use in the context of road tunnel safety management. The most appropriate approach should be selected by considering the respective advantages and disadvantages in the context of a specific situation. The selection should reflect the nature of the problem, the required depth of assessment and the available resources. It has to be taken into account that quantitative methods (e.g. simulations or statistical analysis) are normally more complex and therefore imply more effort for the analysis than qualitative methods (e.g. expert judgements). Furthermore, quantitative methods require specific quantitative input data which may not be available or sufficient, or may not be of the quality required. In addition, it has to be considered that methods cannot be chosen arbitrarily; certain risk evaluation and risk analysis methods have to be used together.

Figure 1.5 illustrates an example of a system-based approach which results in risk values for an overall system to be estimated. The risk assessment is performed for the whole tunnel system investigated on the basis of the risk values of the system (expected value, FN curve). A typical application of a system-based approach might be the evaluation of different additional safety measures including ventilation in terms of their influence on risk.

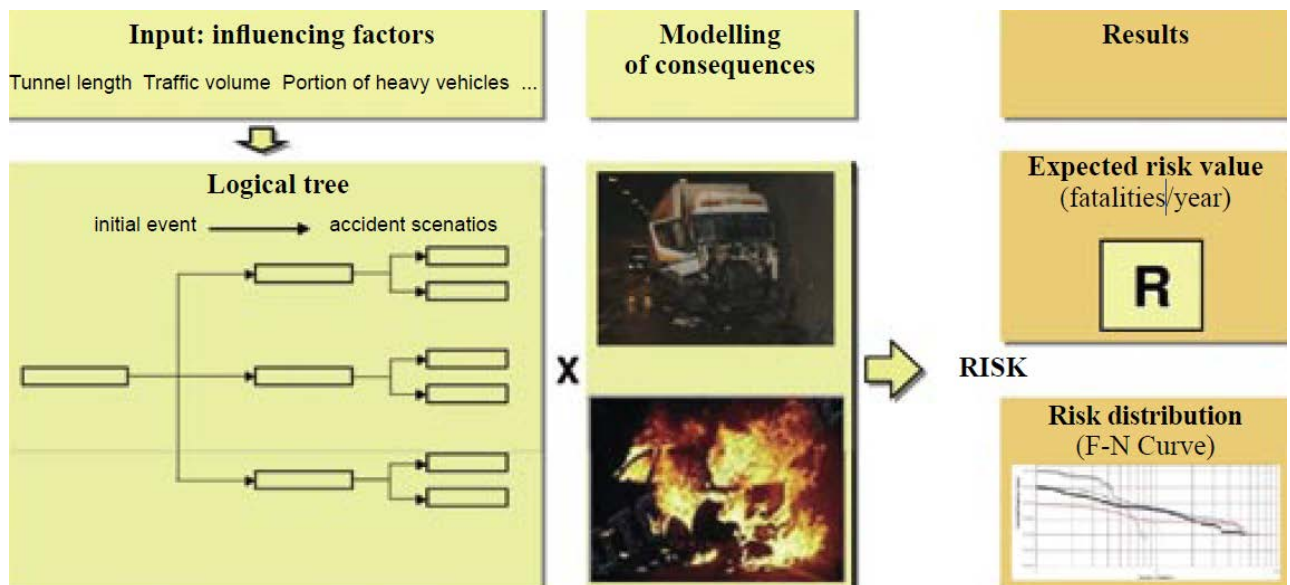


Figure 1.5 Example of system-based approach to risk analysis [2]

Another method is a scenario-based approach for which a set of relevant scenarios is defined, the probability of each scenario is estimated and the possible resulting consequences are analyzed. The risk assessment is done separately for each single scenario on the basis of its characteristic indicators (e.g. frequency of scenario, parameters describing effects and consequences of scenario).

Experience shows that the question of risk evaluation and the definition of what level of risk is acceptable is a significant and debatable part of risk management. In the US, risk evaluation is often used for existing tunnels ventilation and other fire life safety systems upgrades. The PIARC report presents the following recommendations for the practical use of risk analysis:

- be aware that whatever method you choose, you are always using a model which is a more or less major simplification of the real conditions. The method can never predict the course of a real event but helps you to make decisions on a sound and comparable basis;
- select the best method available for a specific problem;
- when selecting a method for a risk analysis, you should also consider how to evaluate the results since the method of risk analysis and the strategy of risk evaluation are not independent;
- whenever possible, use specific data for quantitative methods. If specific data is unavailable, at least check the origin of the data you intend to use (are the conditions relating to infrastructure, traffic, etc. similar to your situation?). Be aware that specific features may be included in a risk model that are not valid for your tunnel;
- for these reasons, risk analysis should only be performed by experts with sufficient experience and understanding of the methods they use;
- be aware that the result of a quantitative risk analysis must be interpreted as an order of magnitude and not as precise number. Risk models inevitably deliver fuzzy results, so risk evaluation by relative comparison (e.g. of various safety measures or of an existing state to a reference state of a tunnel) may improve the robustness of conclusions drawn.

The procedure for a risk analysis can be divided into the following three steps:

- hazard identification: Systematic process to identify and structure all relevant hazards, and to analyze their correlating effects;
- probability analysis: Determination of the probabilities of relevant events/scenarios;
- consequence analysis: Investigation of consequences of relevant scenarios

The simplified flowchart in Figure 1.6 illustrates the main steps of the risk assessment process. It shows the main typical components of the risk assessment process only;; more detailed diagrams, supplementary components and additional mutual links may be needed when analyzing the safety of a particular tunnel.

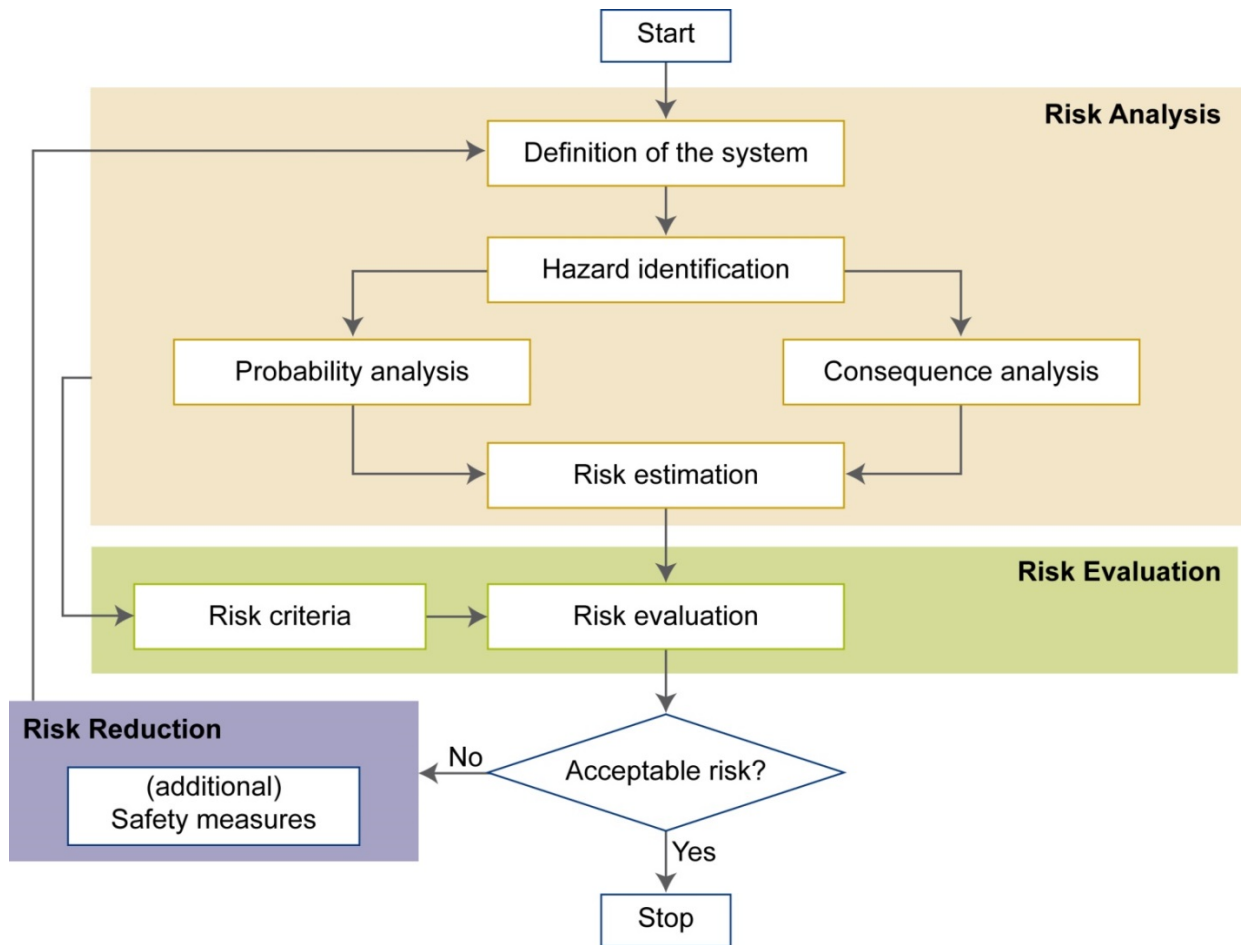


Figure 1.6 Flowchart of the procedure for risk assessment [2]

The concept of tunnel safety is schematically shown in Figure 1.7. Although life safety must always be of paramount importance, the severe operational risks presented by a long term tunnel closure cannot be underestimated.

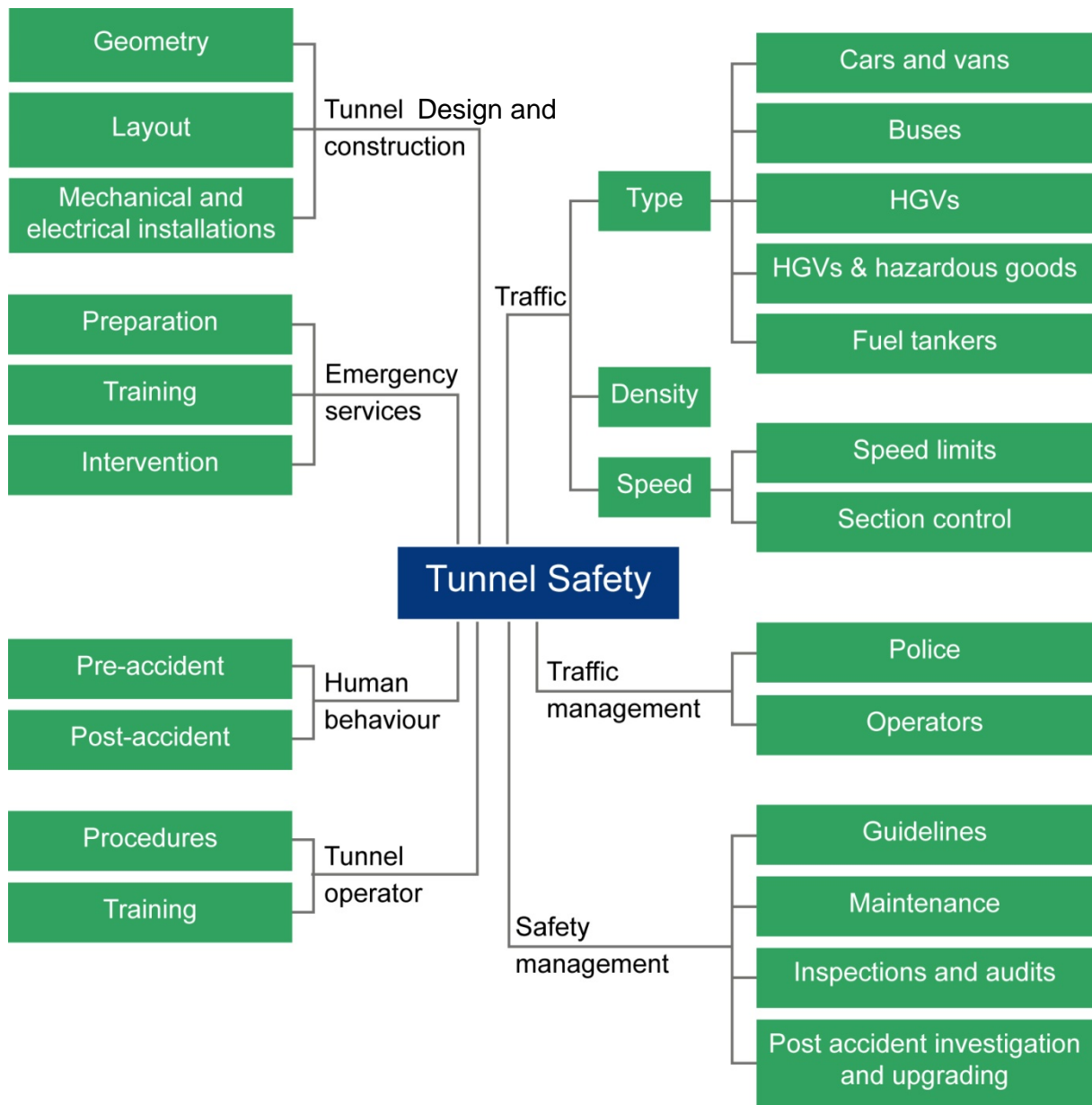


Figure 1.7 Tunnel safety concept.

Risk assessments are regularly used to determine how to prioritize limited resources (such as money and expertise) in the systematic improvement of some aspect of safety performance, such as ventilation systems upgrades. “Unfortunately, the techniques described as “risk analysis” are often either mathematically flawed or applied so poorly that the results are, at best, meaningless and at worst highly destructive to sound decision making” [2] resulting in untenable environment, large scale loss of life and structural compromises. Without adherence to the fundamental mathematical principles of “risk analysis” by practitioners almost any outcome is possible – by accident or by design. The seriousness of this situation is compounded by the fact that there is a temptation to use these techniques as a substitute for professional judgement – and not limit its use as a tool to assist in the decision making process to upgrade existing tunnels. Understanding the limitations of risk analysis is fundamental to

using its tools and techniques to effectively understand and manage risk. There is a shortage of data for such risk analysis to be conducted in many tunnel contexts. This lack of data makes proving the results are wrong, or even discovering the nature of the errors, extremely difficult – except at the conceptual level [2].

- PIARC Road Tunnels: Operational Strategies for Emergency Ventilation (2011R02) [15]. This study provides guidelines for ventilation systems, emergency ventilation control and operation.
- PIARC Systems and Equipment for Fire and Smoke Control in Road Tunnels - 05.16.B (2007) [16]. This study complements the 1999 PIARC report “Fire and Smoke Control in Road Tunnels” and provides in-depth details of fire specific equipment and emergency operation issues.

Chapter 1 discusses the basic principles of smoke and heat development at the beginning of a fire, including the role of the ventilation system during the self-evacuation and firefighting phases. Chapter 2 discusses tunnel fire safety concepts including safety during the design, construction, operation, and maintenance phases. It discusses risk analysis and introduces the “ALARP” approach, which aims to ensure that risks are “As Low As Reasonably Practicable”. The key operative word is “reasonably”. The interpretation of “reasonably practicable” inevitably depends on the point of view of the person making the judgment (operator, user, lawyer, etc.). Such an approach is limited by the fact that a cost/benefit analysis will never be positive if comparing investments in tunnel with other investments in the open air. Chapter 3 discusses lessons learned from recent tunnel fires including the Mont-Blanc, Tauern, and the St. Gotthard Tunnel fires. Chapter 4 discusses different types of ventilation systems and ventilation equipment. Chapter 5 discusses emergency exit and escape route design and cross passage configurations. Chapter 6 is on fire equipment including fire detection and fire suppression. Chapter 7 addresses issues related to the structural resistance of the tunnel to fire. Chapter 8 is on the operations and control including preventive maintenance, inspection, and testing.

- PIARC Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations [17].

The purpose of this report is to provide decision makers and designers with information to assist them with their understanding of the parameters of FFFS, and to provide guidance on whether or not to include FFFS in their road tunnels. The report looks at international experience based on current installations, test programs, and real life incidents. In some countries, risk and cost benefit analyses are used to consider the application of FFFS as a measure to assist in making infrastructure both safer and more durable in the event of an incident. However, for various political, economic, technical, and social reasons, it is recognized that they may not be the most appropriate measure to adopt in all circumstances. These reasons can include where a road tunnel has a dedicated fire service to provide a similar response in a timely manner, where government directive asserts that FFFS will not be applied in that particular country’s tunnels, or where FFFS will not be maintained and operated to the degree of reliability and availability required. Where FFFS are installed, it is essential that they be correctly designed, installed, integrated, commissioned, maintained, tested, and operated with a high level of reliability and availability, so that the system is available for use as required.

The role of FFFS for road tunnels is to provide facilities for tunnel owners and operators to assist with the early suppression and subsequent management of fires. In this manner, the consequences of a fire event to tunnel users, the tunnel infrastructure, and the societal impact due to the disruption to the wider road network can be mitigated. Their installation enables the fixed infrastructure within a tunnel to address fires more quickly and more easily than if incident responders had to provide and deliver alternate systems to the fire site to respond to the event.

As FFFS are part of the tunnel infrastructure, they allow fire control to be initiated from a remote location automatically, semi-automatically, or manually. This provides advantages in that FFFS allow:

- fires to be addressed in a timely manner, even before the fire brigade arrives at the incident site;
- delivery of sufficient water to the fire site such that control or suppression of a fire occurs before the fire develops into a full scale conflagration;
- the fire brigade to manage the fire incident without putting themselves at risk by being in the near vicinity of a fire; and
- the fire brigade to fully extinguish the fire once it has been suppressed, if required.

Properly designed, installed, integrated, commissioned, maintained, tested and operated FFFS will:

- provide early suppression and control of a fire event;
- retard the fire growth rate, inhibiting the combustion process and reducing the heat output;
- remove heat from the environs of the fire by cooling the surrounding area during an incident;
- limit the potential for fire to spread between vehicles;
- extend the available escape time for tunnel users;
- improve overall tenability for fire fighters, enabling them to respond to the event more effectively;
- reduce the likelihood and extent of structural damage;
- limit the severity and extent of damage to tunnel systems and equipment;
- allow the asset to return to service in a shorter period of time following a fire; and
- return the external road network to full integrity in a shorter period of time following a fire.

When deciding whether or not to install any type of FFFS, the following must be examined:

- the functions and roles of FFFS in the safety concept;
- life safety;
- asset protection and the protection required to assure the availability of the transport link;
- flexibility for additional traffic regimes such as Dangerous Goods Vehicles (DGVs);
- firefighting response;
- the ability to adequately operate and maintain the system, including the roles, positions, and responsibilities of the stakeholders;
- the installation capital cost and/or life cycle cost, as well as the cost benefit from installing FFFS;

- system reliability and redundancy; and
- sustainability, as this may also be a factor in the decision.

The report discusses fire modeling and specifically Computational Fluid Dynamics (CFD) to accurately model many aspects of tunnel fire safety. There have been several full-scale test programs that have been used to perform comparisons of various aspects for CFD modelling. The challenges are in the areas of pyrolysis, combustion, and spray modelling including wall impingement. The phenomenon of pyrolysis is very complex. However, approximate models can be applied in some scenarios. This corresponds to the highest uncertainty in CFD modelling of FFFS. Obtaining accurate solutions is much more challenging than gas-phase calculations for tunnels because the gas and liquid phases must be treated separately and a number of sub-models, such as those accounting for inter-phase mass, momentum, and heat transfer, have to be carefully selected and verified.

In summary, CFD models with FFFS and a prescribed HRR can be used with a high degree of confidence to predict temperatures, radiative heat flux, and smoke behavior in regions remote from the immediate fire. Methods exist to predict the interaction of FFFS with the HRR. However, these methods involve more complex physics, a greater range of length scales, and are influenced by uncertainty in the actual fire geometry. As such, the prediction of HRR and combustion product yields using CFD is an evolving area of practice.

- Other International Documents including European and United Nations (UN) documents which are the result of international projects sponsored by the European Union to address tunnel safety issues after tragic tunnel fire events include:
 - European Thematic Network Fire in Tunnels (FIT) Report (2005) [18]. FIT provided a European platform for the dissemination and exchange of up-to-date knowledge and research on fire in tunnels. FIT consisted of 33 members from 12 European countries. The aim was to optimize research efforts and to release recommendations on design fires for tunnels. Additionally, FIT had an objective to develop a European consensus for fire safety design on the basis of existing national regulations, guidelines, codes of practice, and safety requirements. The objective included defining the best practices for tunnel authorities and fire emergency services on prevention and training, accident management and fire emergency operations. Among other reports, it provided the best practices for fire response management.
 - UN Recommendations on Safety in Road Tunnels, United Nations Economic Commission for Europe, 2001 [19]. Tunnel safety factors are summarized in four groups (road users, operation, infrastructure, vehicles) and safety measures and guidelines are provided.
 - UK Highways Agency BD78 - Design of Road Tunnels (1999) [20]. This document established criteria for the evaluation of basic tunnel ventilation and fire and life safety systems design. It provided guidelines on fire size, smoke stratification, interaction between firefighting operation and ventilation, and the applicability of a fire suppression system.

Several recently developed national Austrian, Australian, Brazilian, and Norwegian guidelines were reviewed and include:

- Australasian Fire Authorities Council (AFAC), Fire Safety Guidelines for Road Tunnels (2001) [21]. This document provides information, guidelines, and requirements for tunnels and tunnel fire safety.
- Austroroads (an association of Australasian road transport and traffic agencies) Guide to Road Tunnels (2010) [22]. This document provides general guidelines and functional requirements for fire safety and ventilation in road tunnels.
- Australian Standard AS 4825 -2011 Tunnel Fire Safety [23]. This document is an informative standard (guidance) which provides a performance based framework to establish the required level of safety. This standard does not set prescriptive requirements, but is based on a risk management approach. It sets requirements for smoke analysis, smoke hazard management for evacuation, and performance requirements for tenability criteria with reference to the SFPE Handbook of Fire Protection Engineering. It provides references to international standards such as NFPA 502.
- Norwegian Public Roads Administration, Road Tunnel (Design Manual, 2004) [24]. This document includes a calculation model for ventilation.
- Austrian Guidelines RVS 09.01.45, 2006 “Constructional Fire Protection in Transportation Buildings for Roads”; RVS 09.02.31, 2014 “Tunnel Equipment, Ventilation, Basic Principles”; and RVS 09.02.41, 2014 “Tunnel Equipment, Fixed Fire Extinguishing Systems”. Wien
- Brazilian Standards on Tunnel Life Safety:
 - 1) Fire protection in tunnels – ABNT NBR 15661:2012. The standard specifies the safety requirements to fire prevention and protection in tunnels, with passengers and or cargo transportation.
 - 2) Tunnel fire safety systems – Signaling and emergency warning ABNT NBR 15981:201. The standard specifies requirements in signaling and emergency warning systems related to fire prevention and protection of tunnels users, cargo transportation and patrimony.
 - 3) Tunnel Fire Safety Systems - Tests, Commissioning and Inspections – ABNT NBR 15775:2014. The standard specifies the requirements for testing, commissioning, and inspecting electrical and mechanical equipment, operation systems, measurement devices, fire detection and firefighting systems and civil constructions related to the fire prevention and protection of users and cargo.

1.2.3 Other publications for Emergency Ventilation Smoke Control in Roadway Tunnels

Other U.S. and international reports and references on tunnel fire safety reviewed for development of the guidelines are:

- 1) FHWA; ASHRAE; Massachusetts Highway Department Memorial Tunnel Fire Ventilation Test Program (MTFVTP) – Test Report 1995 [25]. This report summarizes the full-scale fire tests conducted with various types and configurations of tunnel ventilation systems and foam suppression systems. This program was financed by the Federal Highway Administration and the Commonwealth of Massachusetts for the Boston Central Artery Tunnel project. The experiments were performed in an abandoned 854 m (2,800 ft.) long road tunnel located in West Virginia. About 91 fire tests were performed with diesel oil pool fires. The obtained heat release rates varied from 10 MW (34 MBtu/hr) for a 4.5 m² (48.4 ft²) area of diesel to 100 MW (341 MBtu/hr) for a 44.4 m² (478 ft²) area of diesel. 1,450 devices were installed in the tunnel, providing about 4 million points of data per experiment. The Memorial Tunnel program performed tests with fire sizes

of 10, 20, 50, and 100 MW (34, 68, 172, and 341 MBtu/hr). These tests were performed with various ventilation systems including:

- Full Transverse Ventilation – Air is uniformly supplied and exhausted throughout the entire length of a tunnel or tunnel section.
- Partial Transverse Ventilation – Either supply air or exhaust air, but not both, is uniformly delivered or extracted throughout the entire length of a tunnel.
- Partial Transverse with Single-Point Extraction – A series of large, normally-closed exhaust ports distributed over the length of the tunnel to extract smoke at a point closest to the fire.
- Partial Transverse with Oversized Exhaust Ports – Normally-closed exhaust ports that automatically open in a fire emergency.
- Natural Ventilation
- Longitudinal Ventilation with Jet Fans

The report concluded that longitudinal ventilation system employing jet fans is highly effective in managing the direction of the spread of smoke for fire sizes up to 100 MW (341 MBtu/hr) in a 3.2 percent grade tunnel. The throttling effect of the fire needs to be taken into account in the design of a jet fan longitudinal ventilation system. Jet fans that were located 51.8 m (170 ft) downstream of the fire were subjected to the following temperatures for the tested fire sizes:

- 204°C (400°F) — 20 MW (68 MBtu/hr) fire
- 332°C (630°F) — 50 MW (170 MBtu/hr) fire
- 677°C (1250°F) — 100 MW (341 MBtu/hr) fire

Air velocities of 2.54 m/sec to 2.95 m/sec (500 fpm to 580 fpm) were sufficient to preclude the backlayering of smoke (movement of smoke and hot gases in the opposite direction of intended ventilation airflow in the tunnel roadway) in the Memorial Tunnel for fire tests ranging in size from 10 MW to 100 MW (34 MBtu/hr to 341 MBtu/hr).

Single-zone, balanced, full-transverse ventilation systems that were operated at 0.155 m³/sec/lane meter (100 ft³/min/lane foot) were ineffective in the management of smoke and heated gases for fires of 20 MW (68 MBTU/hr) and larger. Single-zone, unbalanced, full-transverse ventilation systems generated some longitudinal airflow in the roadway. The result of this longitudinal airflow was to offset some of the effects of buoyancy for a 20 MW fire (68 MBtu/hr). The effectiveness of unbalanced, full-transverse ventilation systems is sensitive to the fire location, since there is no control over the airflow direction.

The two-zone (multi-zone) transverse ventilation system that was tested in the MTFVTP provided control over the direction and magnitude of the longitudinal airflow. Airflow rates of 0.155 m³/sec/lane meter (100 ft³/min/lane foot) contained high temperatures from a 20 MW (68 MBtu/hr) fire within 30 m (100 ft) of the fire in the lower elevations of the roadway and smoke within 60 m (200 ft).

The spread of hot gases and smoke was significantly greater with a longer fan response time. Hot smoke layers were observed to spread very quickly, from 490 m to 580 m (1600 ft to 1900 ft), during the initial two minutes of a fire. Natural ventilation resulted in the extensive spread of smoke and heated gases upgrade of the fire, but relatively clear conditions existed downgrade of the fire. The spread of smoke and heated gases

during a 50 MW (171 MBtu/hr) fire was considerably greater than for a 20 MW (68 MBtu/hr) fire. The depth of the smoke layer increased with fire size.

For the tests, a flat ceiling was built in the tunnel at a lower height than the arched tunnel roof. A significant difference was observed between smoke spread with the ceiling removed (arched tunnel roof) and with the ceiling in place. The smoke and hot gas layer migrating along the arched tunnel roof did not descend into the roadways as quickly as in the tests that were conducted with the ceiling in place. Therefore, the time for the smoke layer to descend to a point where it poses an immediate life safety threat is dependent on the fire size and tunnel geometry, specifically tunnel height. In the Memorial Tunnel, smoke traveled between 290 m and 365 m (950 ft and 1200 ft) along the arched tunnel roof before cooling and descending toward the roadway. The loss of visibility caused by the movement of smoke occurs before a temperature that is high enough to be debilitating. In all tests, exposure to high levels of carbon monoxide was never more critical than exposure to smoke or temperature.

The effectiveness of the aqueous film forming foam (AFFF) suppression system that was tested was not diminished by high-velocity longitudinal airflow [4 m/sec (787 fpm)]. The time taken for the suppression system to extinguish the fire, with the sprinkler heads located at the ceiling, ranged from 5 seconds to 75 seconds.

The maximum temperatures experienced at the inlet to the central fans that were located closest to the fire [approximately 213 m (700 ft) from the fire] were as follows:

- 107 °C (225°F) — 20 MW (68 MBtu/hr) fire
- 124 °C (255°F) — 50 MW (171 MBtu/hr) fire
- 163 °C (325°F) — 100 MW (341 MBtu/hr) fire

In a road tunnel, smoke management necessitates either direct extraction at the fire location or the generation of a longitudinal velocity in the tunnel that is capable of transporting the smoke and heated gases in the desired direction to a point of extraction or discharge from the tunnel. Without a smoke management system, the direction and rate of movement of the smoke and heated gases are determined by fire size, tunnel grade (if any), pre-fire conditions, and external meteorological conditions.

The program report shows that balanced, full transverse ventilation is ineffective at controlling smoke and temperatures when fires are above 20 MW (68 MBtu/hr). Being able to effectively control temperatures when fires are below 20 MW (68 MBtu/hr) depends on the fire location. However, if the transverse ventilation system is modified to be a two zone system, it can have the capability to control temperature and smoke for a 20 MW (68 MBtu/hr) fire positioned at different locations along the length of the tunnel.

- 2) SOLIT2 Safety of Life in Tunnels, Annex 3 Engineering Guidance for Fixed Fire Fighting Systems in Tunnels, 2012 [26]. The Safety of Life in Tunnels project was sponsored by the German Government. Over 50 large scale tests were performed. Extrapolating from free-burn data, the researchers calculated that the fire load of a heavy goods vehicle with idle pallets could grow to 180 MW (614 MBtu/hr). Water mist systems reduced the heat release rate to 20-50 MW (68-171 MBtu/hr). SOLIT2 is the engineering guidance for a comprehensive evaluation of tunnels with fixed firefighting systems (FFFS) using the example of water based FFFSs.

- 3) Requirements and Verification Methods of Tunnel Safety and Design, SP Technical Research Institute of Sweden, 2012 [27]. This report discusses the fundamentals of performance-based fire safety design in tunnels.
- 4) Tunnel Engineering Handbook, edited by J. Bickel; T. Kuesel and E. King, 1996 [28]
- 5) The Handbook of Tunnel Fire Safety, edited by A. Beard and R. Carvel, London, 2005 [29]
- 6) Tunnel Fire Dynamics, edited by Hauker Ingason, Ying Zhen Li and Anders Lonnermark, Sweden, 2014 [30]. This book provides an overview of the dynamics and developments of fires in tunnels. It provides guidelines for calculation of important design parameters and referred to in the following chapters.

2 ROAD TUNNEL FIRES

2.1 MAIN DESIGN FIRE PARAMETERS

The design fire parameters used for the design of tunnel emergency ventilation and fire life and safety systems have a significant impact on the tunnel design and users' safety. The key criteria are the fire size, heat release rate, fire growth/decay rate, smoke production, resultant temperatures and fire duration. Emergency ventilation system design and operation depends on numerous factors of which the most important are tunnel geometry, types of vehicles and cargos, fire scenario considered, and the main design fire parameters.

NFPA 502 [1] provides a list of factors to consider as part of an engineering analysis which is also updated and expanded with every NFPA 502 review cycle based on recent experience. The current list of factors includes:

1. Users of the facility
2. Restricted vehicle access and egress
3. Fire emergencies ranging from minor incidents to major catastrophes
4. Fire emergencies occurring at one or more locations inside or in close proximity to the facility
5. Fire emergencies occurring in remote locations at a long distance from emergency response facilities
6. Exposure of emergency systems and structures to elevated temperatures
7. Traffic congestion and control during emergencies
8. Built-in fire protection features, such as the following:
 - a. Fire alarm and detection systems
 - b. Standpipe systems
 - c. Water-based firefighting systems
 - d. Ventilation systems
 - e. Emergency communication systems
9. Facility components, including emergency systems
10. Evacuation and rescue requirements
11. Emergency response time
12. Emergency vehicle access points
13. Emergency communication
14. Vehicles and property being transported
15. Facility location, such as urban or rural (risk level and response capacity)
16. Physical dimensions and configurations, including road-way profile
17. Natural factors including prevailing wind
18. Anticipated cargo
19. Impacts to buildings and landmarks near the facility
20. Impacts to facility from external operations and/or incidents
21. Traffic operating mode unidirectional, bidirectional, switchable, or reversible

Each of the above parameters has an impact on anticipated fire parameters, fire severity, and emergency ventilation and other fire life safety systems needed for the tunnel.

Table 2.1 was developed for NCHRP Synthesis 415, Design Fires in Road Tunnels (2011) [3] and summarizes the main design fire variables and provides the typical range for variables. The table illustrates that time dependent design fire variables depend on a number of factors to be studied.

Table 2.1: Design fire variables [3]

Time Dependant Design Fire Variables	Values Range	Design fire variables are a function of:
Fire Size - Maximum FHRR	1.5 – 300 MW [1] (5 – 1020 MBtu/hr)	Type of vehicle (cars, buses, HGV, Tanker; Alternative fuel)
Fire Growth Rate (slow, medium, fast, ultra fast)	0.002 – 0.178 kW/sec ² as high as 0.331 kW/sec ² measured at one test. 20 MW/min linear fire growth rate has been used for several tunnel projects where Flammable and Combustible Liquid Cargo were allowed to pass through the tunnel	Type of cargo including bulk transport of fuel
Fire Decay Rate	0.042 – 0.06 (min ⁻¹) (Note that this parameter is often ignored for conservative evaluations)	Fire detection system and delay in activation of FLS systems
Perimeter of Fire	Car – truck perimeter or pool of liquid fuel spill	Ventilation profile
Maximum Gas Temperature at Ceiling	110 °C – 1350 °C (212 °F – 2462°F) (higher with new energy carriers)	Fire suppression system
Fire Duration	10 min – 6+ days	Tunnel geometry
Smoke and Toxic Species Production Rate	20 – 300 m ³ /sec (42 – 640 kCFM)	- tunnel width, height, cross-section, length
Radiation	From 0.25 to 0.40 of total heat flux up to 5125 W/m ² (1625 Btu/hr/ft ²)	- tunnel volume (available oxygen)
Flame Length	Up to full tunnel height	- shape of tunnel, grade
		- location of exits
		Tunnel drainage system

The magnitude and development of a fire depends on the:

- Vehicle combustion load (often called the fuel load)
- Source of ignition

- Intensity of ignition source
- Distribution of the fuel load in the vehicle
- Fire propagation rate, which could be dependent on many factors including ventilation
- Tunnel and its environment

Specification of a design fire may include the following phases:

- Incipient Phase - Characterized by the initiating source, such as smoldering or flaming fire
- Growth Phase - Propagation spread potentially leading to flashover or full fuel involvement
- Fully-Developed Phase - Nominally steady ventilation or fuel-controlled burning
- Decay Phase – Declining fire severity
- Extinction Phase - Point at which no more heat energy is being released

When there is a fire that involves new types of energy carriers, it can lead to explosions (BLEVE) with catastrophic consequences. The field of new energy carriers is very diverse and constitutes many different fields of research. However, while they do not necessarily carry higher risks, they represent new scenarios and imply new risks.

NFPA 502 provides reference to the fire size and time to reach the maximum fire heat release rate based on the type of vehicle. The maximum fire heat release rate and fire growth rate could be reduced if a fixed fire suppression system is used for tunnel protection and is activated in a timely manner. Factors that should be considered when designing the fire and life safety systems include the following:

- The successful management of tunnel fires requires that fires are detected quickly and accurately while they are still at a controllable size (in the order of 1 – 5 MW [3 – 17 MBtu/hr]). Accurate fire detection is critical in preventing fire spread and fire growth. If a fire is detected early, the fire protection system could suppress a small fire or take a larger fire under control, not allowing it to grow further or spread to other vehicles.
- Additional considerations are to be given to the impact of the fixed fire suppression system on smoke stratification and visibility.

The design process may expect the ventilation and fire safety design engineer to consider the following questions to come to a decision on the fire scenario and design fire parameters for ventilation and other fire life safety system's design:

- The chart in Figure 2.1 presents a simplified process and is used for considerations of the design process only. Numbers presented in the diagram are for illustrative purposes only. The final decision process for design fire parameters should include other factors and follow NFPA 502 requirements previously identified in the document.

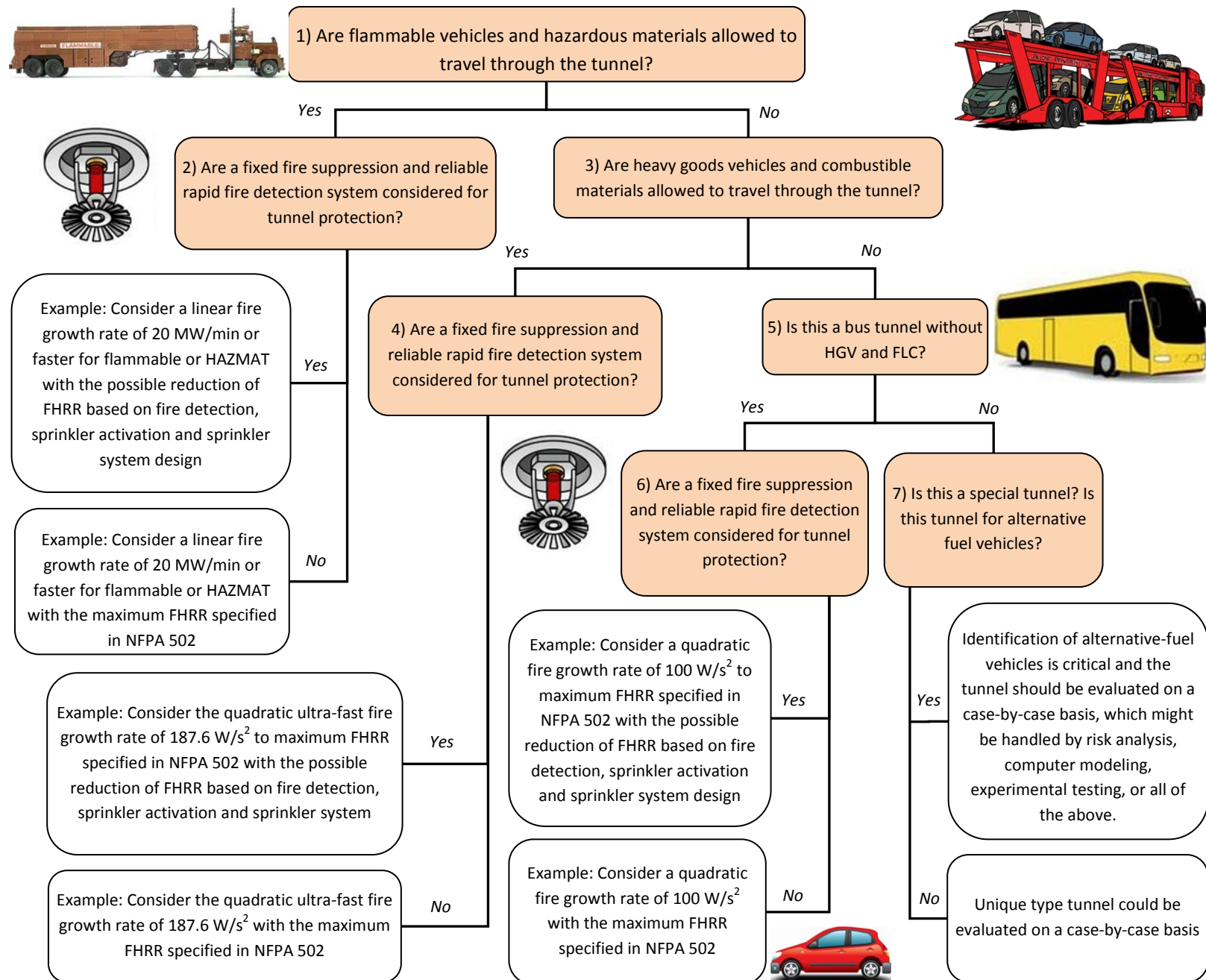


Figure 2.1: Sample decision making chart on design fire parameters.

Note that t^2 fire growth rate is typical while linear fire growth rate in the above example is used for illustration of verity of fire growth to be considered.

2.2 IMPACT OF FIRE SIZE ON SMOKE MANAGEMENT REQUIREMENTS

An objective of the tunnel ventilation system is to control and/or extract smoke and heated gases and provide a non-contaminated environment for egress of tunnel users. Another objective is to support firefighting and rescue operations. In both cases, the primary goal is to control smoke and hot gases as the result of fire. The amount of smoke and heat generated depends on the fire size. It is often assumed that the smoke generation and heat generation rates are proportional to the fire size (note that this may not always be the case as smoke is a product of incomplete combustion and depends upon the combustion mechanism of burning materials). In general, the larger the fire size the more combustion products the fire produces and hence, more air is required to control smoke and hot gases. However, this ratio is not linear.

There are two commonly used concepts for smoke management in road tunnels to achieve a smoke-free environment for egress. They are:

1. Longitudinal ventilation concept - directing smoke along the tunnel in the opposite direction of egress. The longitudinal ventilation concept is achieved by producing air velocity that meets or exceeds the critical velocity along the tunnel which prevents smoke backlayering. The critical velocity depends on the fire size as described below.
2. Extraction ventilation concept - extracting smoke at the fire location and relying on smoke stratification (see Figure 2.2 - left) to allow for egress under the smoke layer. The extraction concept is achieved by maximizing the exhaust rate in the ventilation zone that contains the fire and by avoiding disruption of the smoke layer by longitudinal air velocities. This concept depends on the smoke production rate which is a function of the fire size. Note that smoke stratification may not occur for fires with relatively small heat production rates (low buoyancy) (see Figure 2.2 - right) and especially when the flame is not visible (for example, rubber tire fires). Also, stratification can be destroyed by airflow passing by the fire site or by a fixed firefighting system. Extraction ventilation systems designed for large size fires should be designed and analysed for both stratified smoke and non-stratified smoke.



Figure 2.2 Diesel fuel pan fire of 5 MW in I-90 tunnel in Seattle (left); Winnipeg Transit Bus on Fire (right)

Critical Velocity. There are two main types of models to estimate critical velocity, the critical Froude model and the non-dimensional model. NFPA 502 currently uses the critical Froude number model [1]. The equation for critical velocity can be found in Annex D of NFPA 502. It shows a direct relationship between the critical velocity and fire size.

The non-dimensional model [30] concludes that the critical velocity tends to be independent of the fire size (fire heat release rate HRR) for large fires (over 100 MW [341 MBtu/hr]). For the small fires, such as from 5 to 30 MW (17 to 100 MBtu/hr), the non-dimensional model critical velocity results are much higher values.

Smoke Stratification. A smoke layer may be created in tunnels at the early stage of a fire with essentially no longitudinal ventilation. However, if a smoke layer is formed, it will descend further away from the fire as the hot smoke and gases near the ceiling cool. If the tunnel is sufficiently long, the smoke layer may descend to the tunnel surface at a specific distance from the fire depending on the fire size (temperature / buoyancy effect), the tunnel shape, air velocity, ambient conditions and the perimeter and height of the tunnel cross-section. The smoke layer can also descend if the smoke generation rate is higher than smoke movement (transportation) along the tunnel flow rate which causes smoke expansion towards the road surface. Typically, as the longitudinal ventilation is gradually increased, the stratified layer will gradually cool and spread throughout the tunnel. The particular dimensionless group, which determines whether a gas will stratify above another, is the Froude number (Fr) or the Richardson number (Ri) [30] which defines mass transfer between layers.

The destratification downstream from the fire is a result of the mixing process between the cold air stream and the hot plume flow created by the fire. The gravitational forces tend to suppress the turbulent mixing between the two different density flows. There is a correlation between the local temperature, the gaseous composition (CO , CO_2 , O_2 , etc.), and smoke (soot, ash, gases and other solid particles) stratification in tunnels. The temperature stratification is not only related to the air velocity but also to the HRR and the height of the tunnel. These parameters can be related through the local Froude number (Fr) or Richardson number (Ri).

Small fires, with relatively low temperatures generated, create less buoyancy in the combustion products, and thus decrease the likelihood of smoke stratification under the tunnel roof than with hotter fires (see Figure 2.2 - right). Three distinct regions of temperature and thus smoke stratification are defined by the Froude number (Fr) or Richardson number (Ri) and are shown in Figure 2.3 [30].

- The first region (region I), when $Fr < 0.9$, results in severe stratification, in which hot combustion products travel along the ceiling. For region I, the gas temperature near the floor is essentially ambient. This region consists of buoyancy-dominated temperature stratification. This region is next to the fire location and allows for motorist evacuation.
- The second region (region II), when $0.9 < Fr < 10$, is dominated by strong interaction between imposed horizontal flow and buoyancy forces. Although not severely stratified or layered, it involves vertical temperature gradients and is mixture-controlled. In other words, there is significant interaction between the ventilation velocity and the fire-induced buoyancy.
- The third region (region III), when $Fr > 10$, has insignificant vertical temperature gradients and consequently, insignificant stratification.

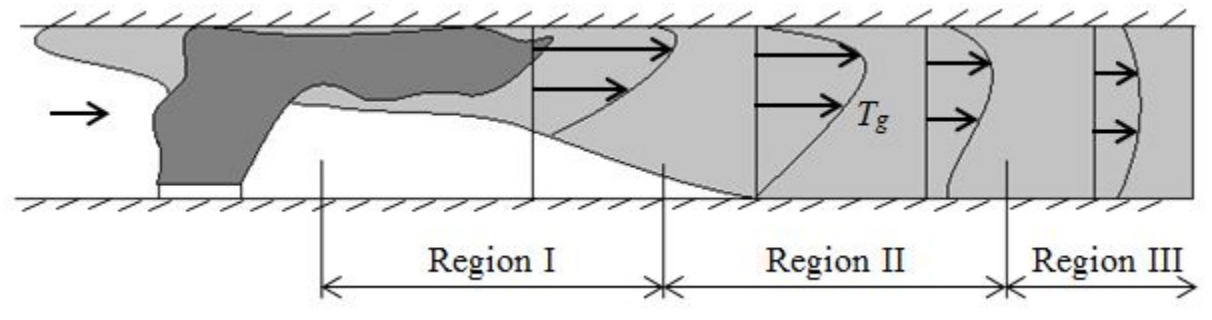


Figure 2.3 Sketch with three stratification regions

Extraction ventilation concept. The main design parameter for smoke extraction is the smoke flow rate produced by the fire. The smoke flow rate depends on the combustion, but in general can be considered to vary nearly linearly with the heat release rate - from about $50 \text{ m}^3/\text{s}$ ($1765.7 \text{ ft}^3/\text{s}$) at approximately 10 MW (34 MBtu/hr), to about $250 \text{ m}^3/\text{s}$ ($8828.7 \text{ ft}^3/\text{s}$) at approx. 150 MW (512 MBtu/hr), as shown in Figure 2.4 [14].

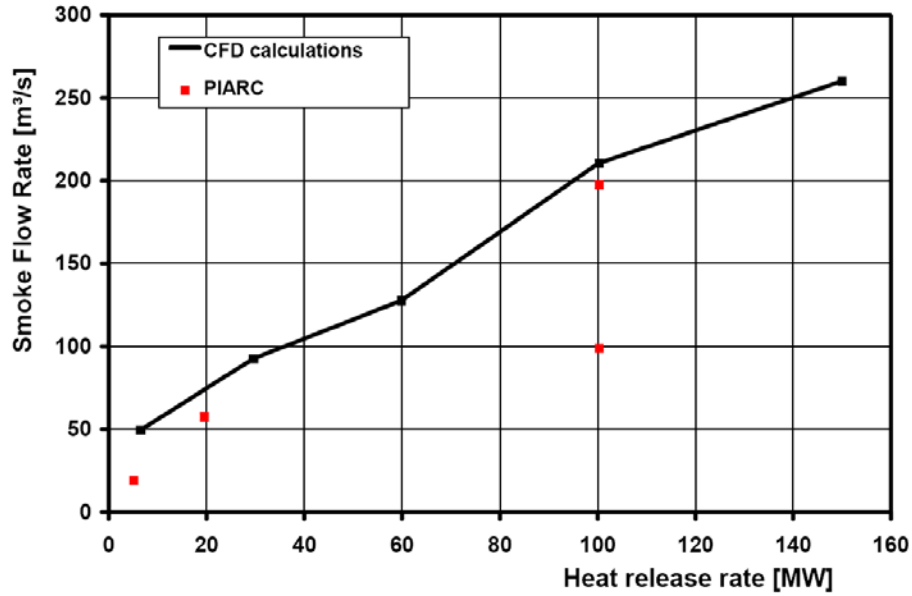


Figure 2.4: Smoke flow rate versus fire heat release rate [18] [31]

Table 2.2 presents smoke production rates, CO and CO₂ published in different literature sources (summarized experimental results and values from standards) [14] [17] [18] [31]. In order to convert the smoke masses produced to smoke volumes, it is necessary to know the smoke temperatures. The theoretical stoichiometric combustion temperature of regular gasoline is about 2000 °C (3632 °F). The real fire temperatures are usually much lower, mainly because the combustion is not stoichiometric or because the smoke mixes with air.

Table 2.2: Smoke, CO₂ and CO production [17]

Burning vehicle	Smoke flow				CO ₂ production	CO production
	[m ³ /s (ft ³ /s)]				[kg/s (lb/s)]	
	PIARC 1987 [32]	RABT 1994 [33]	EUREKA tests [34]	CETU (1996) [31]	EUREKA-tests [34]	
Passenger car	20 (706)	20 – 40 (706 -1412)	-	20 (706)	-	-
Passenger van (plastic)	-		30 (1059.4)	30 (1060)	0.4-0.9 (0.88–2)	0.020-0.046 (0.04–0.1)
2 – 3 passenger cars	-		-	30 (1060)	-	-
1 van	-		-	50 (1765)	-	-
Bus/truck without dangerous goods	60 (2120)	60 – 90 (2120 – 3180)	50 - 60 (1765 – 2120)	80 (2825)	1.5-2.5 (3.3–5.5)	0.077-0.128 (0.17–0.28)
Heavy goods vehicle	-		-	50 – 80 (1765 – 2825)	6.0-14.0 (13.2–30.9)	0.306-0.714 (0.67–1.57)
Gasoline tanker	100 -200 (3531 – 7063)	150 –300 (5300–10600)	-	300 (10600)	-	-

Along with smoke production rates, buoyancy and other factors described above, additional consideration should be given to the impact of fixed firefighting systems on smoke stratification. Smoke management is usually achieved using tunnel ventilation equipment and is impacted by the fire suppression system considering that fixed firefighting system can reduce the fire size and fire growth rate. Reduction of the fire size should reduce overall smoke production and propagation; however fixed firefighting systems may cause incomplete combustion, which may increase smoke production. Once the fire size and possible fire scenarios are determined, the requirements of ventilation and fire suppression systems can be determined based on the length of the tunnel and traffic mode along with

other tunnel operational characteristics. Table 2.3 represents a simplified example of considering the fire safety risks for tunnels and the required fire life safety systems to mitigate those risks, such as tunnel ventilation and fixed fire suppression systems. This table is for illustrative purposes only and cannot replace engineering analysis which may include risk analysis based on traffic volumes and other factors discussed previously. (e.g. long mountain tunnel with low traffic volumes bears less risk than a shorter urban tunnel with high traffic volumes).

Table 2.3: Simplified example of tunnel fire safety risk and fire life safety system needs based on the tunnel length and traffic conditions

Category	Tunnel Length [ft]	Uni-directional traffic			Bi-directional traffic		
		w/HGV; w/FLC	w/HGV; no FLC	no HGV; no FLC	w/HGV; w/FLC	w/HGV; no FLC	no HGV; no FLC
X	< 300	No Ventilation; No Fire Suppression			No Ventilation; No Fire Suppression		
A	300 - 800	Ventilation (suppression likely to protect structure)	No Fire Suppression (Ventilation questionable)	No Ventilation; No Fire Suppression	Ventilation; (suppression likely to protect structure)	No Fire Suppression (Ventilation questionable)	No Fire Suppression (Ventilation unlikely)
B	800 - 1000	Ventilation (suppression likely to protect structure)	No Fire Suppression (Ventilation likely)	No Fire Suppression (Ventilation questionable)	Ventilation, Fire Suppression	Ventilation; (suppression likely to protect structure)	No Fire Suppression; Ventilation required
C	1000 - 3280	Ventilation, Fire Suppression	Ventilation; (suppression likely to protect structure)	No Fire Suppression (Ventilation likely)	Ventilation, Fire Suppression	Ventilation; (suppression likely to protect structure)	No Fire Suppression; Ventilation required
D	> 3280	Ventilation, Fire Suppression	Ventilation, Fire Suppression	No Fire Suppression; Ventilation required	Ventilation, Fire Suppression	Ventilation, Fire Suppression	No Fire Suppression; Ventilation required

Notes:

Tunnel categories X; A; B ; C ; D are defined by NFPA 502 [1] and are illustrated in Figure 3.11 discussed in Section 3.2.2 of these guidelines.

FLC - Flammable liquid cargo (e.g., fuel tankers)

HGV - Heavy goods vehicles (trucks)

Colours represent the level of risk and hence relative cost of fire life safety systems, with Green being the least risky and least expensive and Red being the most risky and most expensive.

Another impact of fire size on tunnel ventilation requirements is related to the ventilation equipment design temperature. This heavily depends on the type of ventilation system and its configuration. Jet

fans and tunnel dampers could be directly exposed to the fire temperature and need to be designed accordingly. This impact is further discussed in Chapter 3 (see Table 3.4)

Tunnel fires significantly increase the air temperature in the tunnel roadway and in the exhaust air duct (if utilized in the design). Therefore, both the tunnel structure, air ducts (where applicable), and ventilation equipment will be exposed to high smoke/gas temperatures. Protection of structural elements from heat is required by NFPA 502 [1]. Loss of structural elements could be life threatening for evacuees; it may also have an impact on the tunnel ventilation system. For example, the jet fan support system should be designed for high temperature exposure. Ductwork should maintain structural integrity. Ventilation equipment, including tunnel ventilation fans, should be designed for high temperature exposure (see Section 3.3).

3 TUNNEL EMERGENCY VENTILATION AND SMOKE CONTROL DESIGN GUIDELINES

The purpose of controlling the spread of smoke and maintaining a tenable environment is to keep people in a smoke-free or survivable environment as long as possible or for at least the duration of evacuation and rescue. This can mean one or both of the following:

- Keep the smoke stratification intact, leaving more or less clean and breathable air suitable for evacuation underneath the smoke layer to both sides of the fire (applicable to bi-directional or congested unidirectional tunnels and is typically achieved by zoned transverse ventilation or single point extraction as discussed in the following sections).
- Completely push the smoke to one side of the fire (preferably applied to non-congested unidirectional tunnels where there are normally no people downstream of the fire and is typically achieved by longitudinal ventilation as discussed in the following sections).

In all situations, people must be able to reach a safe place in a reasonably short amount of time (before tenability is in jeopardy) and cover a reasonably short distance. Emergency exits should be provided wherever necessary.

Cross passages and egress stairs are common and an effective method of providing means of egress. Spacing between cross passages and egress stairs shall be determined using egress and tenability analysis and depends on tunnel ventilation and FFFS activation and operation [16] and shall not exceed spacing limited by NFPA 502 Standard [1]. The standard states that “Emergency ‘exits’ shall be pressurized in accordance with NFPA 92”, which means that they should be free from smoke in order to provide a safe evacuation path to evacuees. To achieve this, an airflow at air velocities greater than critical velocity that prevents smoke from getting into the cross passages/egress stairs shall be developed by the ventilation system with the direction of flow from the cross passage into an incident tunnel. This requires design analysis, but typically air velocities of not more than 2 m/s out of the cross passage/stair door(s) is sufficient when all desired egress doors are open. When the doors are closed the cross passages/egress stairs should be pressurized such that the force to open the doors fully, when applied to the latch side, should be as low as possible but in accordance with NFPA 502 [1], which states that the force to open shall not exceed 222N (50 lb.). Typically, such a requirement could be met with cross passage pressurization fans utilizing VFDs, barometric relief dampers, and sliding doors used in the path of egress.

While multiple fire events at different tunnel locations at the same time are theoretically possible, the probability of such a catastrophic event is extremely low and has not happened so far. It is a good engineering practice to design the systems for a single fire event at a time, while emergency response plans may need to consider possible responses to more severe events.

3.1 TYPES OF ROAD TUNNEL VENTILATION SYSTEMS

Choosing the type of ventilation system is one of the most important decisions when designing a tunnel. While every situation has its unique features, some general conclusions can be drawn about the relative usefulness and efficiency of the various types of ventilation systems for smoke control.

There are several types of natural and mechanical ventilation systems that have been used in road tunnels. Options for mechanical ventilation include longitudinal ventilation and transverse ventilation (fully transverse, semi-transverse, combination of, or modifications of the schemes discussed below). A longitudinal ventilation system achieves its objectives through the flow of air along the tunnel roadway, while a full or semi- transverse ventilation system achieves its objectives by means of continuous uniform distribution, collection, or simultaneous distribution and collection of air throughout the length of the tunnel roadway. There are also many combinations of different types of basic ventilation such as single point extraction, ventilation with intermediate shafts, etc. Each option is described in detail in this section.

Natural ventilation relies on natural phenomena and the traffic piston effect to ventilate the tunnel. Tunnel air is never still, as there is always some airflow caused by the piston effect and/or wind and other natural factors. During a fire emergency, it is expected that traffic will not be allowed to enter the tunnel and trapped vehicles will be stopped behind the fire location. The resulting piston effect generated by exiting residual vehicles leaving the tunnel and entering emergency vehicles will be minimal. However, adverse winds may have a significant impact on the tunnel airflow. Natural ventilated tunnels rely primarily on atmospheric conditions to maintain airflow and provide a satisfactory environment. The main factors affecting the environment are the pressure differential created by differences in elevation, the ambient air temperature, and wind effects at the boundaries of the facility.

The external effects that contribute to a difference in portal pressures are:

- portal entrance and exit pressure losses;
- the stack (chimney) effect (in tunnels that have nonzero grades, particularly those with portals at different elevations, a temperature dependent effect usually referred to as "the chimney effect" is often considered. Air will flow through a chimney, in a direction from the lower portal to the higher portal or vice versa, because of the difference between the weight of the column of air inside, the chimney (tunnel) and an equivalent column of air outside);
- atmospheric pressure differences (referred to the same elevation datum); and
- local wind effects at the portals.

These effects combine to create a net external force acting on the tunnel air volume. The momentum equation is a balance of the following factors:

$$\left\{ \begin{array}{l} \text{Effect of wind;} \\ \text{barometric pressure} \\ \text{and temperature} \\ \text{differences} \end{array} \right\} + \{\text{Piston Effect}\} = \left\{ \begin{array}{l} \text{Friction losses in} \\ \text{the tunnel plus} \\ \text{exit and entrance} \\ \text{losses} \end{array} \right\}$$

Pressure losses at the entrance and exit portals are due to the sudden change in flow cross sectional area and can be expressed as the product of a loss coefficient and the local flow dynamic pressure at the portal. At the flow exit, the pressure loss (static or total) arises from the abrupt expansion into an essentially infinite cross section and is given by

$$\Delta P_{\text{Flow Exit}} = \xi_e \frac{\rho U^2}{2}$$

The exit loss coefficient ξ_e is normally equal to 1.0 for the turbulent flows and cross section geometries found in most tunnels. The pressure loss is equivalent to the local dynamic pressure. Exit portals that have curved rather than square corners (such as a bell-mouthed exit) will generally not reduce the exit loss coefficient.

The pressure loss at the flow entrance is due to the abrupt contraction from an essentially infinite flow area to the tunnel cross sectional area. This loss can also be expressed as the product of a loss coefficient and the local dynamic pressure:

$$\Delta P_{\text{Flow Entrance}} = \xi_i \frac{\rho U^2}{2}$$

The entrance coefficient depends on the portal shape. For a flat square-edged entrance the value of ξ_i is usually taken as 0.5 with the resultant pressure loss equal to one-half of the entrance dynamic pressure. The entrance loss coefficient can be reduced significantly by rounding the portal corners (streamlining) to achieve 'a smooth bell-mouthed entrance. Streamlining reduces some of the flow separation to values as low as 0.1 for turbulent flows. For certain protruding entrance configurations, such as designs where the tunnel walls and roof extend significantly outward from a large sloped wall or hillside, entrance loss coefficients greater than 0.5 and up to 0.75 can be expected.

If the portals are at different elevations, the hydrostatic difference in elevation head should be considered. For example, for long tunnels through mountain ranges, significant changes in barometric pressure (referred to the same elevation datum) can result in a static pressure difference given by the equation:

$$\Delta P_{\text{Atm}} = P_{\text{AtmO}} - P_{\text{AtmL}}$$

In road tunnels that have nonzero grades, particularly those with portals at different elevations, a temperature dependent effect usually referred to as "the chimney effect" is often considered.

$$P_{\text{AtmO}}^{zo} - P_{\text{AtmL}}^{zl} = \Delta P_{\text{elev}} + \Delta P_{\text{atm}}$$

Typically, air will flow through a chimney in a direction from the lower entrance to the higher entrance usually because of the difference between the weight of the column of air inside the chimney (tunnel) and an equivalent column of air outside the chimney (tunnel). If the interior temperature is higher (e.g., due to the heating effect of vehicles or soil conditions), then the tunnel air density will be lower and the chimney effect will promote air flow in the direction of increasing elevation. Conversely, if the tunnel air temperature is lower than that outside (e.g., due to heat transfer to cooler tunnel walls) the tunnel air density will be higher and the chimney effect will promote airflow in the direction of decreasing elevation.

If it is assumed that the temperature variation inside the tunnel is approximately linear with elevation, then the force of the chimney effect can be calculated as:

$$F_{\text{Chimney Linear}} = gA\rho_r T_r (Z_l - Z_o) \left\{ \frac{\ln \frac{T_{\text{Atm}_L}}{T_{\text{Atm}_O}}}{T_{\text{Atm}_L} - T_{\text{Atm}_O}} - \frac{\ln \frac{T_L}{T_O}}{T_L - T_O} \right\} [8]$$

where

T_O and T_L are the absolute temperatures of the tunnel air near the entrance and exit portals respectively;
 $\rho_r T_r$ – are the air density and absolute temperatures at a reference state (low portal);
 Z_l ; Z_o – are the elevations at the exit and entrance portals;
 T_{Atm_L} ; T_{Atm_O} – the atmosphere absolute temperatures outside the exit and entrance portals.

External winds at tunnel portals can vary considerably in magnitude and direction as a function of time. Moreover, the net effect of wind action on the tunnel air flows depends considerably on the portal geometry and the surrounding topography. Portal winds can have significant favorable or unfavorable effects on road tunnel ventilation and must be considered. The difference of pressure caused by outside winds can be evaluated using the following simplified equation of Bernoulli:

$$\Delta P = \frac{1}{2} k \rho \omega^2 \sin \phi_w [35]$$

where

ΔP – represents the pressure induced by wind;
 ρ – the air density;
 ω – the wind speed typically obtained from the wind rose for the area or from the local wind data;
 ϕ_w – the angle of wind with respect to the tunnel axis;
 k – a design parameter which depends on the configuration of the portals. This effect was studied by W. Blendermann [36]

Table 3.1: Configuration of tunnel portals tested by W. Blendermann [36]

ADDITIONAL FEATURE	PORTAL ABOVE GROUND LEVEL	PORTAL BELOW GROUND LEVEL	
		WITH VERTICAL SIDE-WALLS	WITH SLOPING BOUNDS
----	Figure 3.2 (a)	Figure 3.2 (d)	*
Dividing wall	Figure 3.2 (b)	Figure 3.2 (e)	*
Light adaptation section	Figure 3.2 (c)	Figure 3.2 (f)	
Dam	*	*	Figure 3.2 (g)

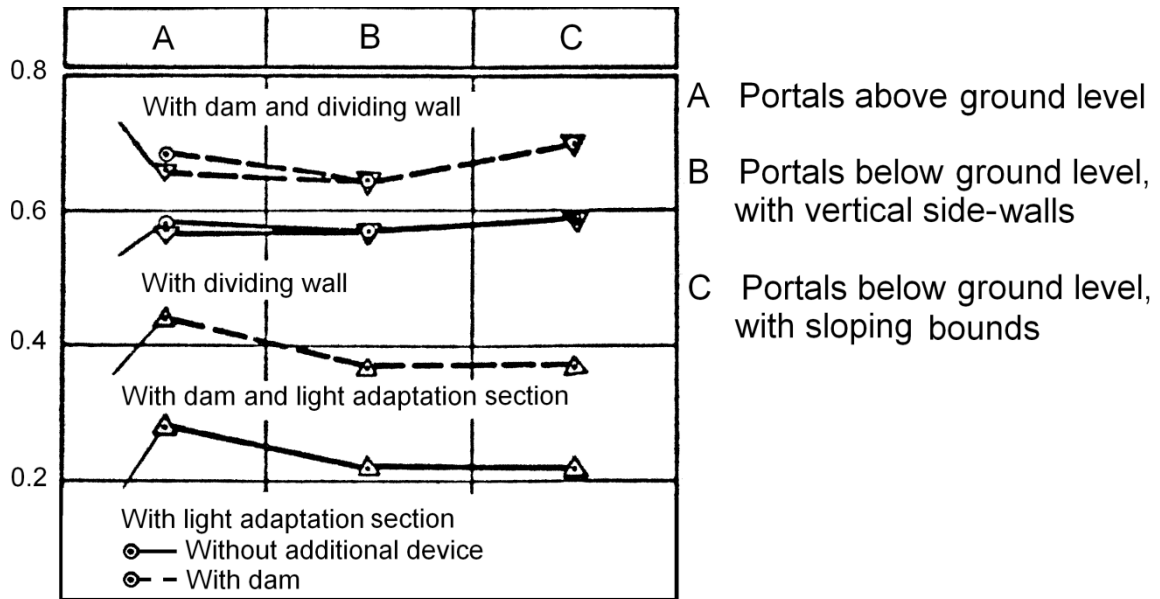


Figure 3.1: Mean wind pressure coefficients [36]

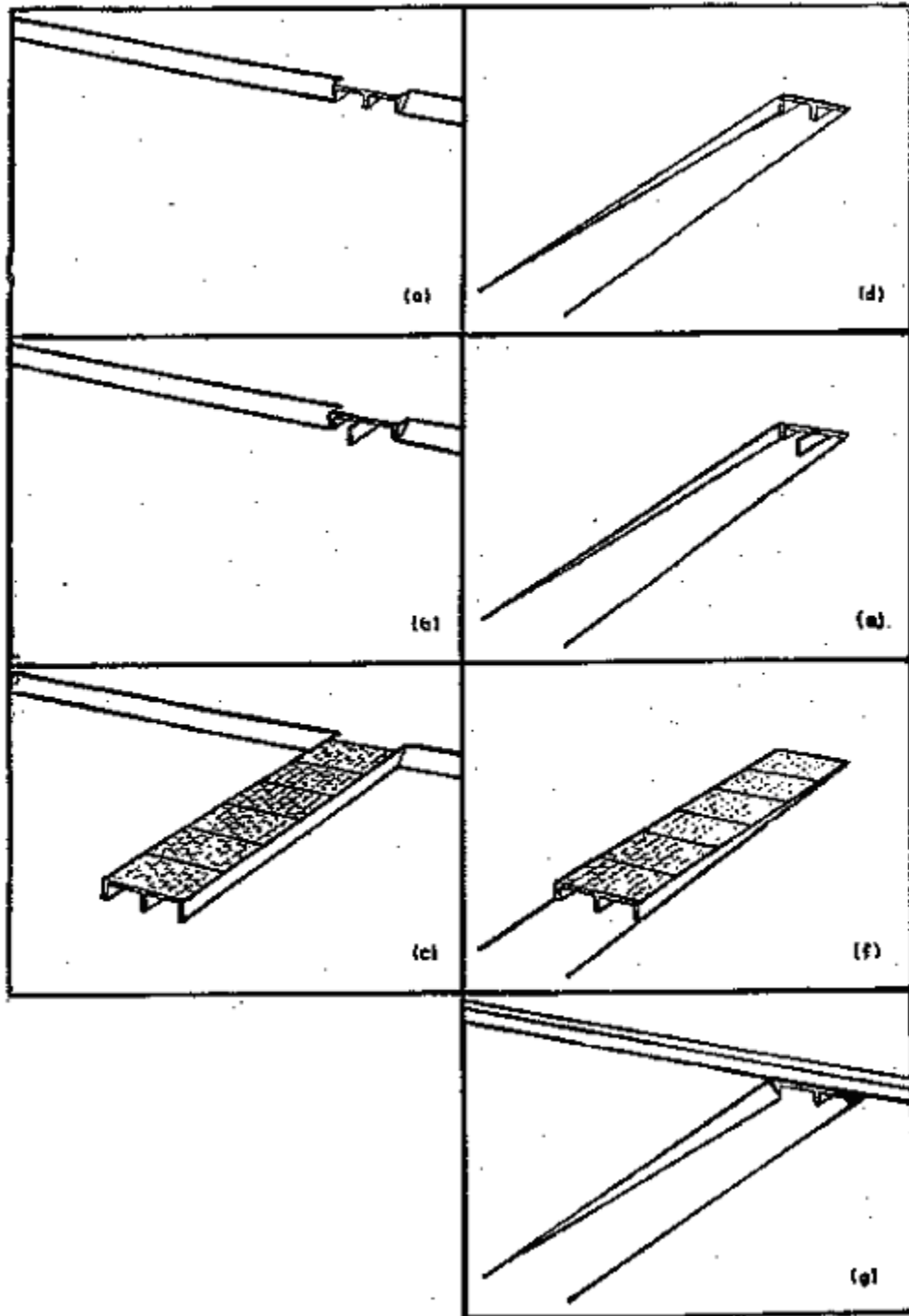


Figure 3.2: Configurations of tunnel portals tested by Blendermann [36]

The orientation of both tunnel portals with respect to the prevailing winds is a very significant parameter. The effective wind resistance (or thrust) is a function of the angle between the direction of the wind and the direction of the air flow entering/exiting the tunnel.

The traffic condition may need to be evaluated. For example, in uni-directional tunnels, the assumption is made that in a fire emergency, the tunnel will be closed for on-coming traffic; some traffic will be trapped behind the fire while traffic downstream of the fire will leave the tunnel. The leaving traffic will cause a residual piston effect, driving smoke and airflow in the direction of travel. Residual air movement, caused by traffic approaching the fire location (piston effect) may also drive the airflow until the traffic movement in the tunnel is halted. The piston effect could be developed by emergency response vehicles as well while they move in the tunnel.

The vehicle drag force F_D and the vehicle drag coefficient C_D are defined by the following expression involving the tunnel air velocity U relative to the vehicle speed V and the vehicle frontal area A_v

$$F_D = C_D A_v \frac{\rho}{2} (V - U)^2$$

The vehicle drag coefficients are measured using wind tunnel tests. Heavy-duty vehicles such as trucks and buses have larger drag coefficients than passenger vehicles typically in the range of 0.6 to around 1.0. This is due to the wide variety of heavy-duty vehicle profiles including cab-over and conventional style tractors and a large number of trailer and bodywork configurations. Average vehicle drag coefficient values of 0.4 for automobiles and 0.75 to 1.0 for heavy duty vehicles have been used in a number of highway tunnel studies.

The equation for naturally ventilated tunnels with uni-directional traffic can be written as:

$$\tilde{C} + \frac{C_D A_v N L}{A V} (V - U)^2 = \left(\xi_i + \xi_e + \frac{\lambda L}{D} \right) U^2 \quad [8]$$

where

\tilde{C} – represents wind, barometric pressure and temperature difference effects;

N – number of vehicles traveling per unit length of tunnel;

L – tunnel length;

D – tunnel hydraulic diameter;

λ - The Darcy coefficient is a function of the Reynolds number and the ratio of the surface roughness to the hydraulic diameter. It is determined from the Moody diagram or the Colebrook equation.

Due to the fully developed turbulent flow and rough walls in tunnels, it can usually be assumed that the Darcy coefficient is a constant for a given tunnel with the variation from tunnel to tunnel primarily due to the type of wall lining used. Values commonly used for the Darcy coefficient in the design of road tunnels are 0.015 to 0.020 for very smooth lining, 0.025 for plain concrete, and 0.03 to 0.05 for bare rock with no lining.

Several aspects must be taken into account for the effects of a tunnel fire on the air flow in a tunnel:

- In the event of a large fire (where buoyancy forces are dominant), the high temperatures induce an increase of air volume (due to expansion) and therefore of air speed, as a result of which the air friction losses increase.
- The density decreases, friction velocity increases, and the overall local losses increase.
- The blockage effect of the fire on the longitudinal airflow produces a supplementary local head loss.

- With steep grades of tunnels, the force of the chimney effect can rise to significant values.

Natural ventilation systems can be very effective for the dilution of pollutants (especially for uni-directional tunnels), but it is difficult to rely upon natural ventilation for safety purposes. In fact, most of the natural ventilation factors are highly variable with time and therefore unreliable.

Because of the number of different parameters that need to be considered in order to decide if mechanical ventilation is to be installed in a tunnel (length, location, traffic, type of vehicles using the tunnel, risks, and so forth), it is not possible at this moment to express universal recommendations about the limits of natural ventilation, particularly the allowable length without mechanical ventilation. NFPA 502 requires analysis of numerous factors to make a decision regardless of the length of the facility [1].

During a fire event with practically zero longitudinal air velocity and no significant grade, the smoke layer expands to both sides of the fire and smoke may spread in a stratified way for up to 10 minutes (to a distance of 400 to 600 m depending upon the tunnel geometry and fire conditions). After this initial phase, smoke starts to mix over the whole cross-section, unless by this time the mechanical ventilation, such as an extraction system, is in full operation. A tunnel that is long or experiences frequent adverse atmospheric conditions requires fan-based mechanical ventilation.

Longitudinal ventilation introduces air into or removes smoke and gases from the tunnel at a limited number of points, primarily by creating longitudinal airflow through the length of the tunnel, from one portal to the other. Longitudinal ventilation can be accomplished either by injection, central fans, jet fans mounted within the tunnel, nozzles (often installed at the portals and called a Saccardo system), or through a combination of injection and extraction at intermediate points. The system must generate sufficient longitudinal air velocity to prevent backlayering of smoke. The air velocity necessary to prevent backlayering over stalled or blocked motor vehicles is the minimum velocity needed for smoke control in a longitudinal ventilation system. This velocity is known as the critical velocity and was discussed previously in Section 2.2.

The limitations of longitudinal ventilation systems are often related to limitations of air velocity in road tunnels (see Section 3.2.1). The limitations on high air velocities are typically driven by normal ventilation requirements for the dilution of concentrations of vehicle emissions during free flowing and congested traffic and are seldom related to fire emergency conditions. Exceptions could be emergency response requirements to limit smoke spread along the tunnel or turbulence that affects the smoke stratification downstream of the fire. This phenomenon is more evident at higher air velocities. Smoke stratification can also be disturbed by the longitudinal slope of the tunnel (especially when air flows downwards) and by vehicles.

Longitudinal ventilation is particularly suited for tunnels with free flowing uni-directional traffic because of the assumption that drivers downstream of the fire are free to escape by continuing to drive towards the exit portal while drivers upstream remain behind the fire. Other types of traffic flow, including bi-directional traffic and uni-directional congested traffic, are better supported by other ventilation schemes. The following chart presents an example of a design process for the selection of the type of road tunnel ventilation system:

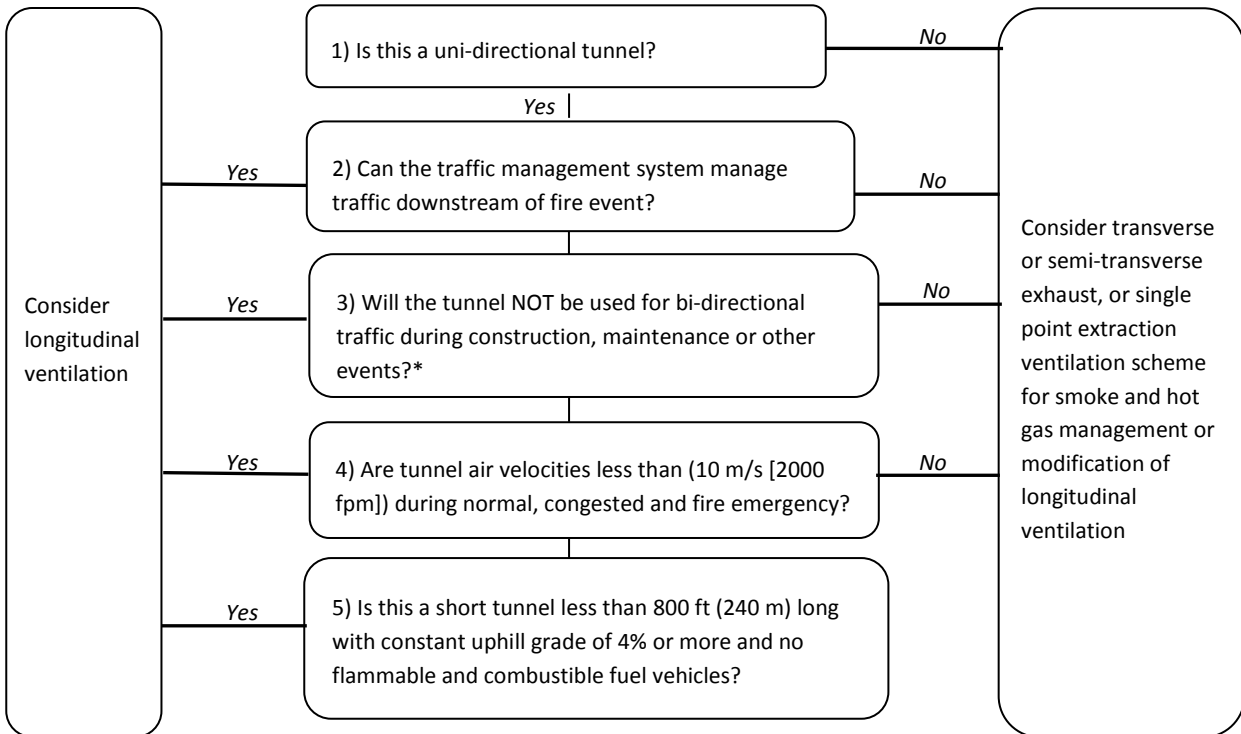


Figure 3.3: Example of design process for consideration of longitudinal ventilation for the road tunnel ventilation system selection

* - In certain cases longitudinal ventilation could be justified for contra-flow traffic.

Numbers presented in Figure 3.3 are for illustrative purposes only. In addition to the factors shown in the figure, the decision process for ventilation scheme selection should include traffic volumes, tunnel location, environmental emission, and additional factors.

One of the common methods of achieving longitudinal ventilation is the use of jet fans and this type of system has been installed in numerous tunnels worldwide. With this scheme, specially designed axial fans (jet fans) are typically mounted at the tunnel ceiling or side niches. This system eliminates the space needed to house large ventilation fans in a transverse ventilation system at a separate structure or ventilation building but may require greater tunnel height or width to accommodate the jet fans so that the fans are outside the tunnel's dynamic clearance envelope. This envelope, formed by the vertical and horizontal planes surrounding the roadway in a tunnel, defines the maximum limits of the predicted vertical and lateral movement of vehicles traveling on the roadway at the design speed. However, as tunnel length increases, disadvantages such as excessive air speed in the roadway and smoke being drawn the entire length of the roadway during an emergency fire event become apparent.



Figure 3.4: Diagram of longitudinal ventilation controlling smoke and hot gases

The increase in pressure necessary to generate or maintain the longitudinal flow in the tunnel is provided by the acceleration of the air flowing through the fan. Although jet fans deliver relatively small air quantities at high velocities (in the range of 25 – 45 m/s [4900 – 8900 fpm]), the momentum produced is transferred to the entire tunnel, inducing airflow in the desired direction. Jet fans are normally rated in terms of thrust rather than airflow and pressure and can be either unidirectional or reversible. It should be noted that the decrease of air density during a fire event results in the lowering of the driving force of the jet fans that work in the hot air. Jet fan sizing is usually limited by the space available for installation in the tunnel (see Section 3.3).

Calculations of jet fan capacity should take into account what air velocities should be sufficient for control of fire smoke. Usually the jet fans are designed to be reversible to allow for first responders to switch the direction of smoke movement after the evacuation is complete. For longitudinal ventilation using jet fans, the required number of fans is defined (once fan size and tunnel airflow requirements have been determined) by the total thrust required to overcome the tunnel resistance (pressure loss), divided by the individual jet fan thrust, which is a function of the mean air velocity in the tunnel. Fan thrust N_s values provided by fan manufacturer can be defined by the equation:

$$N_s = C_1 \rho Q U$$

where

C_1 – empirical correction factor;

ρ – air density;

Q – air volume;

U – air velocity

The effective thrust imposed by the jet fan on the tunnel is based on the jet velocity relative to the tunnel air velocity. There is also an impact from the tunnel walls and from other parallel jet fans installed within the same group of fans. The effective fan thrust N_e can be written:

$$N_e = N_s \left(1 - \frac{U_t}{U_j}\right) C_2 C_3$$

where

U_t – tunnel air velocity;

U_j – jet velocity developed by jet fan;

C_2 – jet fan installation factor which depends on wall and/or ceiling proximity, jet fan inclination angle and tunnel niche effect;

C_3 – group of fans installation factor as a function of fan spacing, fan proximity to the entrance and exit portals.

If the jet fan is placed in the center of the tunnel tube, vertically and horizontally, the installation factor will equal 1. However, such installation is impossible. The closer the jet fans are installed to the tunnel walls and ceiling, the stronger the wall roughness impacts the effective fan thrust. In order to create maximum space for the traffic in a road tunnel, the fans are often installed close to the ceiling. A considerable portion of the jet energy is lost to wall friction. The highest losses occur when the fan is installed in niches.

Jet fan installation in niches should be accounted for by a reduction in the coefficient of efficiency of the impulse force of the fan to determine the longitudinal airflow in the tunnel. Moving the impulse fan further into this niche increases its eccentricity, until the fan is situated completely outside the tunnel tube profile. The additional losses due to wall friction will grow correspondingly. As a result, jet fans can lose up to 30% of their efficiency due to niche installation. [37] Howden Standard 66-05.150 provides loss coefficients for niche installations.

The total thrust developed by a number of fans in a tunnel is the sum of the individual thrusts. The number of fans required is equal to the total tunnel thrust required divided by the effective fan thrust.

Jet fans must not be installed too close to each other. Jet fans installed longitudinally should be installed at a sufficient distance away from the next jet fan installation location to allow the tunnel air velocity profile to become approximately uniform at the following location, which is at least 7 to 10 tunnel hydraulic diameters (or sometimes identified as 100 fan diameters) apart so that the jet velocity does not affect the performance of the downstream fan. Otherwise, the jet stream of the preceding fan would not have fully decayed before being drawn into the suction side of the next fan. To ensure that the jet fans yield maximum efficiency, the jet stream from any fan must be fully decayed before it reaches the next jet fan.

Jet fans installed side by side should be at least two fan diameters (centerline to centerline) apart. In this case they can be approximated as a single jet fan of equivalent cross sectional area. Reduction of spacing between jet fans should be accounted for in the jet fan installation factor. The axial installation distance between fans could be reduced or the installation factor improved if flow deflectors are installed.

Jet fans installed close to the portal (at a distance less than 200 feet [60 m] or 40 fan diameters – see Figure 3.6) will lose their efficiency and will not produce the desired amount of air flow in the tunnel in a fire emergency. When jet fans are installed at a distance of less than 150 feet [46 m] or 30 fan diameters (see Figure 3.5 and Figure 3.6) from the portal and direct air out of the tunnel, air recirculation in the portal area will occur.

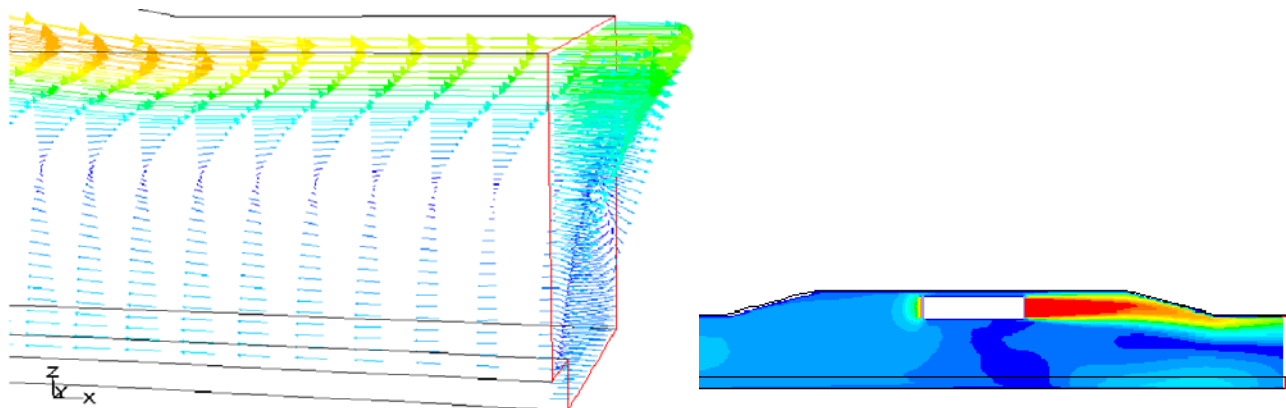


Figure 3.5 Velocity vectors and pressure for jet fans installed close to the portal and blowing out of the portal [38]

Figure 3.6 shows an example of the tunnel airflow rate reduction in percentage as the result of the jet fan installation location proximity to the tunnel portal. The values depend on the tunnel geometry and Figure 3.6 is for illustration purposes only.

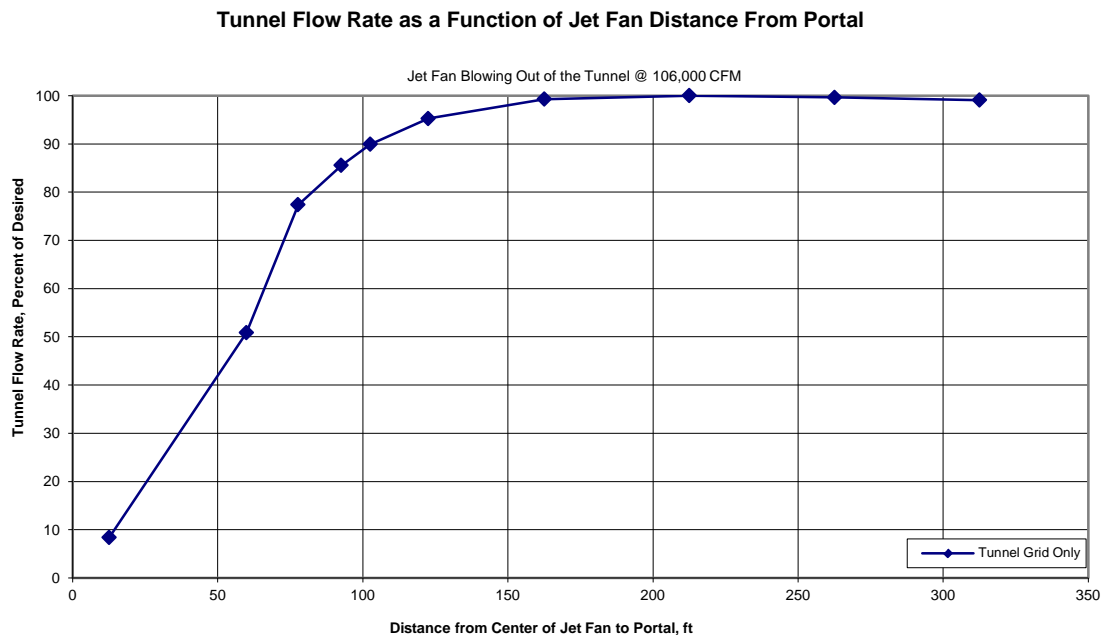


Figure 3.6 Tunnel flow rate as a function of center of jet fan distance from the exit portal (example) [38]

Also, operating jet fans close to the fire is not recommended as air recirculation typically occurs locally at the jet fan locations. The recirculation could destroy stratification and draw smoke and hot gases in the opposite direction of the intended air flow.

Jet fans are often fitted with integral silencers and deflecting vanes to achieve an acceptable sound level and improve air flow development in the tunnel. Silencers and vanes cause additional resistance to the airflow which results in a reduction of fan thrust. Jet fans can have several speeds or be supplied with adjustable (variable) speed drives for reduced fan operation and power consumption during normal operation such as during night time when ventilation needs are lower compared to in emergency mode.

Longitudinal ventilation through injection using a high-velocity Saccardo nozzle. The Saccardo nozzle functions on the principle that a high-velocity air jet injected at a small angle to the tunnel axis can induce a high-volume longitudinal airflow in the tunnel. The phenomenon of air adhesion to the surface of the structure is used to induce secondary air movement in the tunnel in the same direction as the primary flow. The amount of induced flow depends primarily on the nozzle area, discharge velocity, angle of the nozzle, and the downstream air resistances. This type of ventilation is most effective with free flow unidirectional traffic flow.

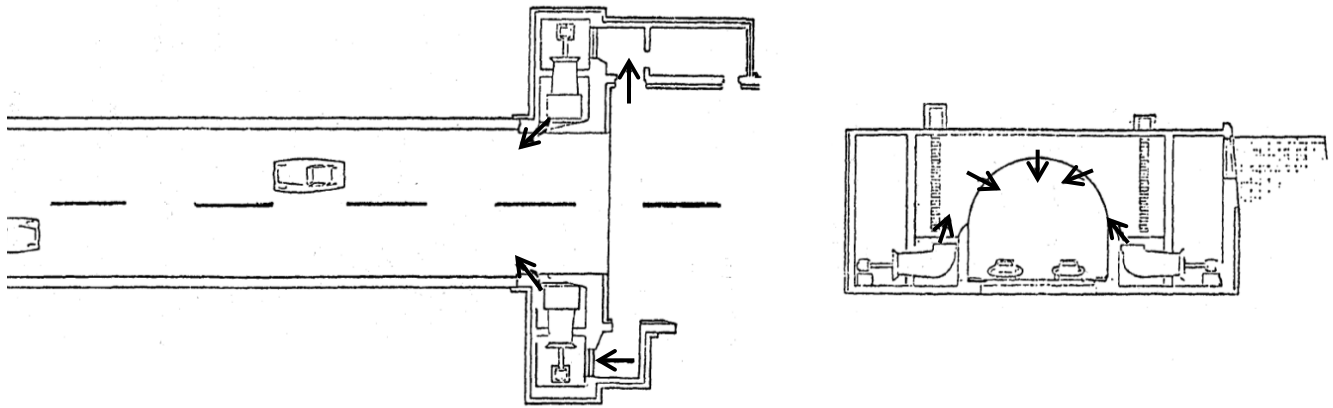


Figure 3.7: Saccardo nozzle ventilation

Saccardo injectors may operate in a flow induction mode (low tunnel air resistance) and in flow rejection mode (high tunnel air resistance). This means there may be flow reversal at the nozzle position with flow exiting the near portal, whereas jet fans always induce flow from one portal to the other. Saccardo nozzles only produce a limited pressure rise and therefore, are suitable for relatively short tunnels unless supported by other ventilation schemes. The Saccardo nozzle ventilation scheme may not be as effective for fires near the injection point, possibly up to a few hundred feet downstream, as air recirculation may occur near the fire. Analysis should be performed to investigate the performance of the system for these fire locations. (See Section 3.3 for Saccardo Nozzle fans)

Another form of a longitudinal ventilation system is one with intermediate ventilation shafts: one for exhaust and one for supply producing a push-pull mode or a single shaft pushing or pulling air from the tunnel. In this arrangement, part of the air flowing in the roadway is replaced by the interaction at the shafts, which reduces the concentration of contaminants downstream of the shaft. This system is most effective in combination with a jet fan or Saccardo system.

This type of longitudinal ventilation system can utilize the Coanda effect, the phenomenon which causes a jet stream to attach to and follow a smooth curved surface, to control the direction of air flow in the tunnel. By providing curved surfaces into the tunnel, an air supply is blown onto the curved surface and the air in the tunnel will flow in the same direction as shown in Figure 3.8.

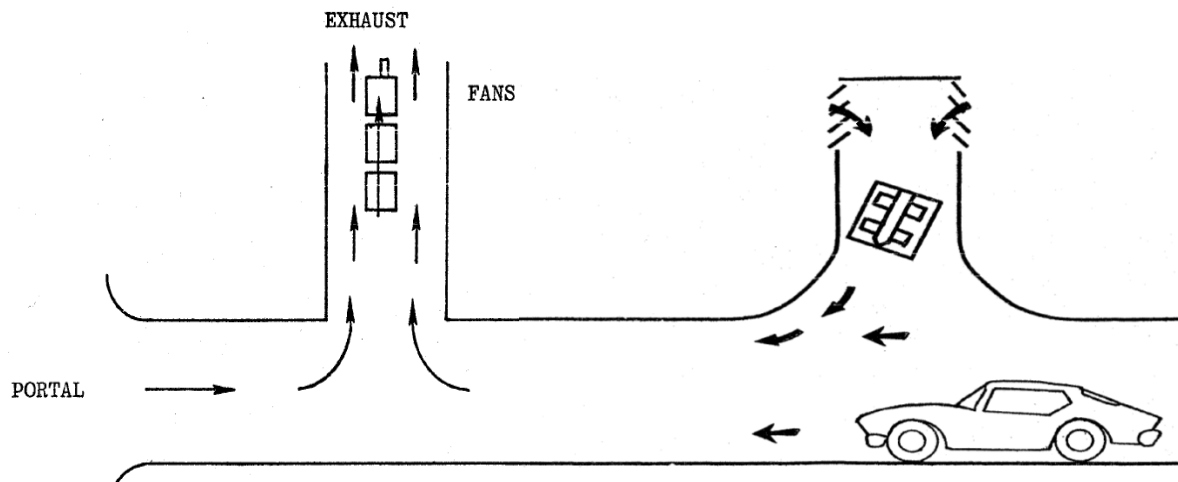


Figure 3.8: Longitudinal ventilation system with shafts utilizing the Coanda effect

Reversible tunnel ventilation fans are often used in ventilation shafts. For emergency ventilation, NFPA 502 requires that “reversible fans shall be capable of completing full rotation reversal within 90 seconds” [1].

A longitudinal ventilation system achieves its objectives through the longitudinal flow of air within the tunnel roadway pushing smoke out the portal. It typically does not require air ducts along the tunnel, while a transverse ventilation system typically does require air ducts. It achieves its objectives by means of the continuous uniform distribution and/or collection of air throughout the length of the tunnel roadway. It is very often that the longitudinal ventilation poses construction costs advantages compared to other ventilation schemes.

Transverse Ventilation is a system that is applied for smoke control when the smoke stratification must be kept intact, leaving more or less clean and breathable air underneath the smoke layer to both sides of the fire while extracting smoke from the fire site (applicable to bi-directional or congested unidirectional tunnels). The stratified smoke is taken out of the tunnel through exhaust openings located at the tunnel ceiling.

With the classic full transverse ventilation system, air is supplied and exhausted all along the tunnel, which requires supply and exhaust ducts along the length of the tunnel and ventilation buildings to house supply and exhaust fans. This system can be found in many old long tunnels. This system can maintain smoke stratification while supplying fresh outside air needed for evacuees.

It is recommended that the fresh air jets enter the tunnel near the road surface. The exit velocity and the distances between the individual jets should be small in order to obtain a uniform fresh air supply. A large tunnel fire creates strong longitudinal airflows to supply the oxygen to the fire. With a continuous transverse fresh air supply along the tunnel, this longitudinal air velocity is small, which minimizes the air mixing with the smoke layer. Fresh air jets entering from ceiling openings are unfavorable for smoke control. When air enters the tunnel vertically at the ceiling, it destroys the smoke layer, inducing smoke into the air jet and thus mix smoke into the fresh air layer. It is recommended to position the fresh air outlets near the road surface. Survivors of the Holland Tunnel fire of 1949 reported that the supply air

saved their lives providing breathable air to a tunnel environment filled with smoke. One recalls trapped firefighters breathing from the curb-level fresh air inlets during the Holland Tunnel fire.

During a fire, exhaust fans in the full transverse system should operate at the highest available capacity and supply fans should operate at a reduced lower capacity (typically 1/2 to 1/3 of the full capacity) with discharge air velocities not to exceed 3 m/s (591 fpm) when there is a fire. This allows the stratified smoke layer (at the tunnel ceiling) to remain at that higher elevation and be extracted by the exhaust system without mixing and allows fresh air to enter through the portals, which creates a breathable environment for both motorist emergency egress and firefighter ingress. Continuous extraction into a return air duct is needed to remove a stratified smoke layer out of the tunnel without disturbing the stratification.

One way to control the longitudinal velocity is to provide several independent ventilation sections. When a tunnel has several ventilation sections, a certain longitudinal velocity in the fire section can be maintained by suitable operation of the individual air ducts. By reversing the fan operation in the exhaust air duct, this duct can be used to supply air and vice versa if the fans are reversible.

Whatever the means of controlling the longitudinal air velocity are, their operation could be preprogrammed according to the location of the fire in the tunnel to assure opening of the required dampers and activation of the required fans, which would reduce the possibility of operator error.

The longitudinal air velocity generated by a transversely ventilated tunnel is usually maintained below 2 m/s (394 fpm) in the vicinity of the fire incident zone. With higher velocities, the vertical turbulence in the shear layer between smoke and fresh air quickly cools the upper layer and the smoke mixes over the whole cross-section; most of the smoke from a medium size fire spreads to one side of the fire (little backlayering) and starts mixing over the whole cross section at a distance of 400 to 600 m (1312 to 1968 ft) downstream of the fire site. This mixing over the cross section can be prevented if the smoke extraction is activated early enough. Additional factors to consider are:

- Vehicles standing in the longitudinal air flow strongly increase the vertical turbulence and encourage the vertical mixing of the smoke.
- In a transverse ventilation system, the fresh air jets entering the tunnel at the floor level induces additional turbulence, which tends to bring the smoke layer down to the road. This is the reason for the recommendation to throttle the fresh air rate from 1/2 to 1/3 of the full capacity, depending on the initial fresh air jet momentum. No fresh air is to be injected from the ceiling in a zone with smoke since this increases the amount of smoke spread and tends to suppress the stratification.

The disadvantage of the classic transverse system is that uniform exhaust along the length of the tunnel is not efficient for complete smoke extraction from the fire site and likely spreads smoke along the tunnel. The amount of exhaust air required for effective smoke extraction from the fire site is very large and impractical to achieve for long tunnels. Supply air could disturb and cool the smoke layer, destroying smoke stratification.

A semi-transverse exhaust system is a modification of the full transverse system with a uniform exhaust air duct along the full length of the tunnel and no supply air. In a fire emergency, the system creates a longitudinal air velocity in the tunnel roadway, and extracts smoke and hot gases at uniform intervals. The disadvantage of this system is that uniform exhaust along the full length of the tunnel does not allow for complete smoke extraction from only the fire site, but spreads smoke along the tunnel. The amount of exhaust air required for effective smoke extraction from the fire site is very large and impractical to achieve for long tunnels.

There are many combinations of different types of basic transverse and semi-transverse ventilation such as single point extraction, ventilation with intermediate shafts, etc. which implement elements of longitudinal and transverse ventilation schemes.

Single Point Exhaust system is a modification of the semi-transverse exhaust system. The spreading of smoke over the whole tunnel length can be prevented by the large extraction of tunnel air directly above traffic with suitable extraction ports or large openings with remotely controlled dampers. This system works best in conjunction with jet fans, or Saccardo nozzles to localize smoke around openings and to prevent smoke driven by natural factors (such as wind and the tunnel grade) from spreading along the tunnel.

In a fire event, single point extraction is achieved at the fire location by remote control of the dampers. To facilitate the maintenance of the equipment, there are systems in use where the large dampers are held by a magnet in closed position. In the fire zone, the magnets release the damper mechanism automatically by command from fire detectors, and the dampers then open by gravity force. However, this system does not allow the openings to close if a smoke plume moves to another place in the tunnel.

Once a design fire and its smoke production rate have been chosen, a permissible length over which the smoke may spread has to be fixed. Depending on the type of exhaust openings (fixed or remote-controlled), the extraction capacity per unit tunnel length in the fire zone is derived. In general, an extraction system needs less total exhaust volume when remote single point extraction dampers are installed than with fixed openings. However, it also has to be considered that in the first phase between the start of smoke spread and full operation of the exhaust system with large dampers, the smoke may have spread over a large distance (such as 1 km or more) from the fire site depending on the fire detection time and ventilation system operation design. Therefore, it may not be sufficient to only open a few exhaust openings near the fire but a minimum exhaust rate along the whole ventilation section could be considered. An extraction strategy has to be developed depending on the type of tunnel and its ventilation system.

The extraction capacity over the length which is permissible for smoke to spread must exceed the smoke rate generated by the fire because the openings will not only exhaust smoke but inevitably some fresh air as well and is discussed in Section 3.5.

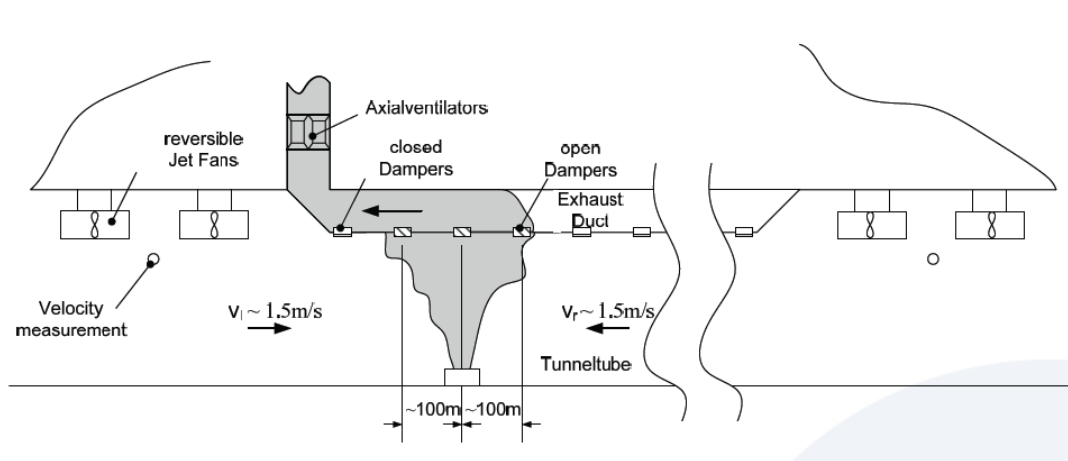


Figure 3.9: Tunnel with a single point extraction system [39]

When fans are located close to or in the exhaust air openings of the single point extraction system, the exhaust fan temperatures must be properly evaluated in the design.

To maintain smoke stratification (see also 3.5), a longitudinal air velocity is required to push smoke to one side of the fire. This can be achieved by jet fans or Saccardo (portal) nozzles. However, to activate the required number of jet fans within a few minutes after fire ignition is a complicated control task due to the turbulent nature of tunnel airflow, a large cross sectional area, changing winds and other natural factors. This requires air velocity measurements averaged over the cross section [40].

- Required detection accuracy +/- 0.3 m/s (60 fpm)
- Short response time
- Proper positioning of sensors

Also, it is important that no jet fan is turned on in or near a place where there is smoke, as this would immediately destroy the smoke stratification.

A semi-transverse supply system is not effective for smoke management as it is unable to maintain smoke stratification or provide smoke extraction at the fire site. It is sometimes used in combination with other systems to achieve longitudinal smoke movement along the tunnel. If a fire occurs in the tunnel, the supply air initially dilutes the smoke. If the system is equipped with reversible fans, supply semi-transverse ventilation should be operated in reverse mode in an emergency so that fresh air enters through the portals and creates a tenable environment for both emergency egress and firefighter ingress. Therefore, a reversible supply semi-transverse ventilation system should preferably have a ceiling supply (in spite of the disadvantages during normal operation) and reversible fans so that smoke can be drawn up to the ceiling during a tunnel fire. The conversion of the duct from supply to extraction must be done as quickly as possible to minimize the spread of smoke.

3.2 TUNNEL VENTILATION SYSTEMS CONDITIONS FOR APPLICATION AND CONFIGURATIONS

Choosing a tunnel ventilation system is a complicated process that should consider both normal and fire emergency design strategies. In the past, tunnel ventilation systems were designed based on normal tunnel operation for vehicle emissions. With the constant reduction of vehicle emissions over the last twenty years, fire emergency conditions become the most important factors for determining the ventilation system in tunnels up to several miles long and this range expands every year.

Many tunnels use the same ventilation system for both normal and fire emergency conditions. When designing and operating such a system, considerations should be given to requirements driven by surrounding infrastructure and pollution concentration controls including portal dispersion concentrations.

The design objectives of the emergency ventilation system should be to control, to extract, or to control and extract, smoke and heated gases. Emergency ventilation system conditions for application are established by NFPA 502:

“In tunnels with bi-directional traffic where motorists can be on both sides of the fire, the following objectives shall be met:

- (1) Smoke stratification shall not be disturbed;
- (2) Longitudinal air velocity shall be kept at low magnitudes;
- (3) Smoke extraction through ceiling openings or high openings along the tunnel wall(s) is effective and shall be considered.

In tunnels with uni-directional traffic where motorists are likely to be located upstream of the fire site, the following objectives shall be met:

- (1) Longitudinal systems
 - a. Prevent backlayering by producing a longitudinal air velocity that is calculated on the basis of critical velocity in the direction of traffic flow.
 - b. Avoid disruption of the smoke layer initially by not operating jet fans that are located near the fire site. Operate fans that are farthest from the site first which are not degraded by exposure to high air temperatures and do not cause de-stratification and recirculation of smoke in the immediate vicinity of the fire.
- (2) Transverse or reversible semi-transverse systems
 - a. Maximize the exhaust rate in the ventilation zone that contains the fire and minimize the amount of outside air that is introduced by a transverse system.
 - b. 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.

Based on the above objectives the transverse ventilation or single point extraction system is more applicable for tunnels with bi-directional traffic or for uni-directional tunnels where motorists are likely to be located to both sides of the fire (unmanageable congested traffic during fire event). Longitudinal

ventilation is likely to be the choice for uni-directional tunnels with managed traffic downstream of the fire. See Figure 3.3 as an example of the design process for consideration of longitudinal ventilation for the road tunnel ventilation system selection.

3.2.1 Tunnel length, geometry and grades

In the past it was considered that longitudinal ventilation was applicable to short road tunnels with uni-directional traffic only, while full transverse ventilation was commonly used for long tunnels or for tunnels with bi-directional traffic. The limitations of longitudinal ventilation systems are often related to the limitations of air velocity in road tunnels. However, these limitations are driven primarily by normal ventilation requirements for concentration of vehicle emissions during free flowing and congested traffic and are seldom related to fire emergency conditions. The exception could be emergency response requirements to limit smoke spread along the tunnel for first responder's ingress.

Tunnel height and width and grades are factors to be considered. There are two impacts of tunnel geometry on ventilation:

- impact of tunnel geometry on “critical velocity”, which has a direct impact on ventilation requirements
- impact of tunnel geometry on ventilation system design

Impact of tunnel geometry on “critical velocity”. The slope of the tunnel has an important influence on the dispersion of the flue gases. In general it can be said that due to the chimney effect, the dispersion velocity of the flue gases increases with the increase in tunnel slope. The longitudinal air velocity's increase will lead to changes of fire HRR and fire growth rate. Section 2.2 discusses critical velocity as the function of fire heat release rate.

Equations for “critical velocity” presented in Annex D of NFPA 502 show the relationship between the tunnel height, tunnel grade and critical velocity. Roadway grade factor is shown in Figure 3.10 and is related to the buoyancy effects. Critical velocity is proportional to the grade factor.

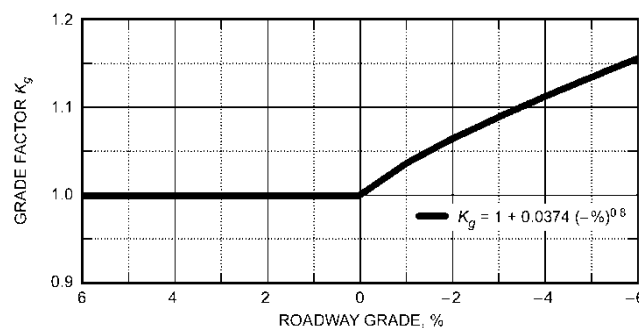


Figure 3.10: Roadway Grade Factor [1] [11]

Smoke from a fire in a tunnel with only natural ventilation is driven primarily by the buoyant effects of hot gases and tends to flow upgrade. The steeper the grade, the faster the smoke moves and thus the higher the velocity needs to be developed by the ventilation system to overcome the buoyancy effect.

One of the key parameters for the fire plume in a tunnel fire is the maximum ceiling gas temperature. The maximum gas temperature in a tunnel fire is mainly related to the effective tunnel height, HRR and ventilation velocity [1] unless buoyancy is impacted by the fire suppression system.

Tunnel Width. The critical velocity in tunnels with aspect ratios of 1 to 3 is approximately independent of tunnel width. When the tunnel aspect ratio (tunnel width to tunnel height) is significantly lower than 1 or greater than 3, the effect of tunnel width may need to be considered. The critical velocity decreases when the width increases. For the aspect ratio lower than one and for high enough HRRs, the critical velocity significantly increases with tunnel width.

The equation that best describes the relationship between fire HRR and the tunnel width W_{tunnel} and fire width W_{fire} is:

$$HRR_{\text{tunnel}} = (B_{\text{tunnel}} / B_{\text{Rune hamar}}) HRR_{\text{Rune hamar}}$$

Where [29, 41, 42]

$$B = 24(W_{\text{fire}} / W_{\text{tunnel}})^3 + 1$$

This equation allows one to estimate the design fire HRR against the values obtained in the Rune hamar tests, considering that $Q_{\text{Rune hamar}} = 203 \text{ MW}$, $W_{\text{fire Rune hamar}} = 2.9 \text{ m}$, $W_{\text{tunnel Rune hamar}} = 7.3 \text{ m}$, or in any other tests. Estimates show that for a 15 m (49.2 ft) wide tunnel, the design fire HRR is about 100 MW (341 MBtu/hr).

Impact of tunnel geometry on ventilation system design

Longitudinal Ventilation. The limitations of longitudinal ventilation systems are often related to limitations of air velocity in road tunnels. The maximum air velocity limitation is driven primarily by normal ventilation requirements for concentration of vehicle emissions during free flowing and congested traffic, and is seldom related to fire emergency conditions. Since the concentration of vehicle emissions increases linearly from the entrance to exit portals with longitudinal ventilation, there is a certain tunnel length that would require airflow in the tunnel of velocities exceeding 2200 fpm (11.0 m/s) in order to maintain acceptable air quality levels at the exit portal.

The maximum air velocity limitation for fire emergencies is set based on the ability of people to walk in a high air speed environment [1]. Intermediate ventilation shafts could be provided to maintain longitudinal tunnel air velocities below 2200 fpm (11.0 m/s). Intermediate vent shafts along the tunnel (if feasible) could extract vitiated air and supply outside air, which expands the limits of longitudinal ventilation length. The emergency response plan could be another limiting factor of longitudinal ventilation scheme.

Longitudinal ventilation is impacted by natural factors, such as portal winds, tunnel grades and portal elevations. Generated airflow should be able to overcome the tunnel chimney effect, sometimes called stack effect, to control tunnel smoke.

Jet fan longitudinal ventilation systems may require greater tunnel height or width to accommodate the jet fans so that they are outside of the tunnel's dynamic clearance envelope. This envelope, formed by the vertical and horizontal planes surrounding the roadway in a tunnel, defines the maximum limits of

the predicted vertical and lateral movement of vehicles traveling on the roadway at design speed. Jet fan sizing is usually limited by the space available for installation in the tunnel, which limits the system's application.

Saccardo nozzle ventilation systems require portal ventilation buildings and significant space at the portal area for Saccardo nozzles installation. This type of system produces a limited pressure rise and therefore is only suitable for relatively short tunnels unless supported by other ventilation schemes, such as jet fans and/or exhaust air shafts.

Longitudinal systems with intermediate ventilation shafts typically require excavations for the shafts, vent buildings and Saccardo nozzles or spaces for jet fan installation.

A brief comparison of the technical and economic features of the two longitudinal impulse ventilation systems reveals that:

- Jet fans have little or no civil engineering costs for installation, but have significant electrical cabling costs.
- Saccardo nozzles (injectors) require expensive civil engineering work to construct ventilation buildings and install the fans at the tunnel portals with limited cabling distribution costs.
- Routine maintenance or emergency repair work on jet fans will usually mean disruption to the normal tunnel service and availability; this is not the case for Saccardo injectors that can be accessed externally.
- Saccardo injectors eliminate electrical cabling within the tunnel; a cost advantage over jet fans.
- Jet fans take up headroom in the tunnel ceiling which limits the effective kinematic envelope of the traffic, whereas Saccardo injectors are located outside the tunnel making them ideal in tightly spaced tunnels.
- Saccardo injectors deliver their thrust at a single point, making them quite vulnerable to local tunnel fixtures. For example, a badly placed traffic sign, LED display, lighting equipment or any significant blockage near the outlet of an injector will cause a dramatic drop in injector performance, whereas jet fans are less affected, as their thrust is distributed.
- Jet fans are not only exposed to high temperatures while operating in the tunnel but also derated when operating at elevated temperatures in a fire environment (lower density), whereas injectors are both safely outside the fire's reach as well as immune to thrust reduction by virtue of using fresh air for primary intake. This offers some advantage in reliability of Saccardo injectors over jet fans.

Transverse ventilation. It could be perceived that transverse ventilation systems have no tunnel length limitations. However, they are limited by the air duct's length to achieve uniform air distribution along the tunnel and by the feasible fan characteristics to produce the required airflow and to develop sufficient pressure to overcome duct losses. The duct cross-sectional area should change along the tunnel length to maintain a uniform ventilation rate. In addition calculating the friction factor of a duct in which there are irregular obstructions to the airflow is challenging. In a vehicular tunnel air duct the term "obstruction" can be used to describe an essential part of the tunnel system, such as water pipes, conduits, cables and etc. The duct length to duct hydraulic diameter ratio is sometimes limited to 300 to

achieve the desired airflow distribution in the tunnel [8]. Multiple ducts each connected to independent fans could be constructed to overcome the technical limitations of one single long duct but costs of such designs would be significantly higher, and in many cases impractical. Tunnel height and width are other factors to be considered for the system selection relying on smoke stratification and protecting tunnel users to both sides of the fire. Tunnel grade is an important factor for the effect of buoyancy and stack effect on smoke and hot gases spread and could either assist or counteract tunnel ventilation.

Tunnel grade. Due to buoyancy effects, natural ventilation results in the extensive spread of smoke and heated gases up-grade of the fire, but relatively clear conditions down-grade of the fire. With a steep grade of the tunnel, the chimney effect can rise to significant values.

With ducted transverse systems depending on the number of traffic lanes and tunnel width, airflow can be concentrated on one side, or divided over two sides. Side walls ducted supply or exhaust may not be practical for over 3 lanes tunnels. Air ducts at the ceiling may require deeper tunnel excavations.

The above relative merits are crucial at the initial concept phase, when deciding on the type of ventilation system for any particular tunnel.

3.2.2 Traffic conditions

Short rural tunnels with uni-directional light traffic with no flammable cargo and no HAZMAT could be justified for natural ventilation. NFPA 502 states that emergency ventilation shall not be required in tunnels less than 1000 m (3280 ft) in length where it can be shown by an engineering analysis using the design parameters of the particular tunnel (length, cross-section, grade, prevailing wind, traffic conditions, types of cargoes, design, fire size, etc), that the level of safety provided by a mechanical ventilation system can be equaled or exceeded by enhancing the means of egress, the use of natural ventilation, or the use of smoke storage, and shall be permitted only where approved by an AHJ.

NFPA 502 provides the categories of road tunnels depending on tunnel length and peak hourly traffic. Ventilation and other fire life safety systems requirements are based on the tunnel category. For example, a tunnel ventilation system is mandatory for all tunnels over 914 m (3000 ft) long with peak hourly traffic of 2,000 vehicles per hour per lane or less, which has the equivalent requirements to a 300 m (1000 ft) long tunnel with a peak hourly traffic of 6,000 vehicles per hour per lane. The tunnel ventilation system is a conditional mandatory for all tunnels over 245 m (800 ft) long with peak hourly traffic of 2,000 vehicles per hour per lane or less, which is equivalent to a 90 m (300 ft) long tunnel with peak hourly traffic of 5,500 vehicles per hour per lane.

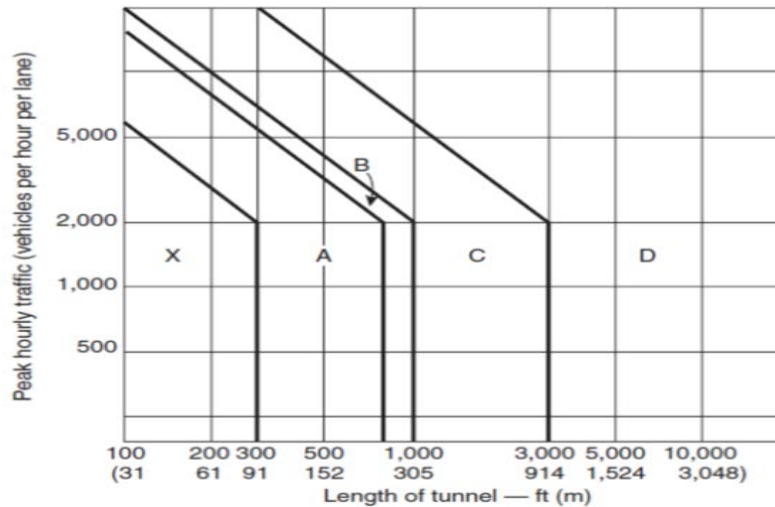


Figure 3.11: Tunnel Categories. Extracted from NFPA 502 (2014 edition) [1]

A tunnel that is long, has a heavy traffic flow, or experiences frequent adverse atmospheric conditions requires fan-based mechanical ventilation. Free flowing uni-directional traffic supports the choice of longitudinal ventilation, while bi-directional traffic or possible congested traffic supports other ventilation schemes (see Figure 3.3 in Section 3.1). In long tunnels with heavy traffic, the use of intermediate ventilation shafts should be considered.

Tunnels with heavy traffic volumes with Flammable Cargo and Heavy Goods Vehicles pose greater risk due to possibilities of a more severe fire event and require more complicated ventilation schemes. A single point extraction system supported by jet fans (or other longitudinal ventilation, such as Saccardo nozzles) is considered the most effective in smoke control for high risk tunnels and where vehicles are trapped on both sides of the fire. This system relies on smoke stratification for fires with significant heat dissipation and smoke capture for all fire types, produces low longitudinal air velocities and does not impact the fire growth and heat release rate as much. However, this system is rather complicated and requires air velocity controls on both sides of the fire. It also needs coordination with sprinkler system activation. Additional means for providing protection of ventilation ducts, such as sprinkler protection of vent ducts, may be needed to avoid structural collapse. Full transverse ventilation is used in extremely long tunnels and in tunnels with heavy traffic volume.

Short tunnels with light traffic and no flammable cargo and HAZMAT materials are less risky. There are some examples of relatively short rural tunnels with light traffic and bi-directional traffic when longitudinal ventilation system with jet fans was justified based on the risk analysis. French and some other international guidelines allow for longitudinal ventilation for short tunnels with bi-directional light traffic conditions. While most of the U.S. tunnels are uni-directional, many would consider using them as bi-directional during construction or maintenance in the parallel tube. Thus, bi-directional mode is often considered for fire design for uni-directional tunnels. Table 3.2 summarizes the requirements for longitudinal ventilation operation in case of fire.

Table 3.2: Longitudinal ventilation operation in tunnels with one-way and two-way traffic

	Evacuation phases	Firefighting phase
Longitudinal ventilation One tube with two-way traffic (not recommended in the U.S. and many other countries)	The smoke stratification must not be disturbed: - longitudinal air velocity quite small - no jet fans working in fire / smoke zone	Avoid backlayering of smoke: - higher longitudinal velocity - direction of airflow adaptable
Longitudinal ventilation with one-way traffic	<u>Normal free traffic:</u> Avoid backlayering of smoke: sufficient longitudinal air velocity in the same direction as traffic flow. <u>Congested traffic</u> , or fire at the end of the queue behind an accident, or one tube used bi-directionally: Same as one tube with bi-directional traffic for the two phases.	

Table 2.3 presents a simplified example of tunnel fire safety risk and fire life safety systems needs based on the tunnel length and traffic conditions. Presence of a fire suppression system is also a factor in risk analysis. Other fire life safety means, such as parallel egress evacuation tunnels, other means of egress and etc, should also be considered for risky tunnels in addition to ventilation requirements.

EU directive requires for tunnels longer than 3000 m (9842 ft), with bi-directional traffic, with a traffic volume higher than 2000 vehicles per lane and with a control center and transverse and/or semi-transverse ventilation, the following minimum measures shall be taken with regards to ventilation:

- Air and smoke extraction dampers shall be installed which can be operated separately or in groups.
- The longitudinal air velocity shall be monitored constantly and the steering process of the ventilation system (dampers, fans, etc.) adjusted accordingly.

PIARC [15] recommends the following principles of smoke control with transverse ventilation systems:

Table 3.3: Transverse ventilation system smoke control strategies [15]

TABLE 2: STRATEGIES FOR SMOKE CONTROL WITH TRANSVERSE VENTILATION SYSTEMS		
CASE	TRAFFIC PRIOR TO INCIDENT	PRINCIPLE FOR SMOKE EXTRACTION
A	Unidirectional traffic <u>without</u> traffic congestion	Flow velocities in direction of traffic upstream of the extraction zone to prevent or at least minimize backlayering of the smoke. On the downstream side, lower flow velocities towards the extraction zone.
B	Unidirectional traffic <u>with</u> traffic congestion	Zero longitudinal velocity at the centre of the extraction zone by having airflow rates from both sides towards the extraction zone. In this case the objective of the airflow is to preserve stratification and, possibly, to confine the smoke to the region of the extraction zone
C	Bi-directional traffic	Zero longitudinal velocity at the centre of the extraction zone by having airflow rates from both sides towards the extraction zone. In this case the objective of the airflow is to preserve stratification and, possibly, to confine the smoke to the region of the extraction zone

For Case B, since the congested traffic would tend to move out of the tunnel, the longitudinal velocity at the extraction zone may be set higher than zero if the information is available to do so.

Without remotely controlled dampers, the smoke is extracted through relatively small openings distributed along a long section. Therefore, the extraction rate near the fire is limited and much lower than using remotely-controlled dampers. Smoke stratification, however, cannot be guaranteed but is more likely to occur when the longitudinal flow velocity is below about 1.5 m/s (300 fpm).

Whether or not dampers can be controlled in the region of the fire, the longitudinal flow has to be controlled in order to ensure the desired flow velocities up- and downstream of the extraction zone. For this purpose, plausibility checks of the flow measurements have to be carried out in order to ensure that the flow measurements are reliable and representative for the actual flow situation in the tunnel.

Interference of the airflow control devices with the smoke extraction should be avoided e.g. by not using jet fans that are situated close to the smoke-extraction zone.

3.3 TUNNEL VENTILATION FANS UTILIZATION AND PLACEMENT

The ability of tunnels to function depends mostly on the effectiveness and reliability of its ventilation system, which is expected to operate effectively under the most adverse environmental, climatic, and vehicle traffic conditions. A tunnel ventilation system should be robust and designed with redundant fan(s) and more than one dependable power source to prevent interruption of service.

The prime concerns in selecting the type, size, and number of fans include the total theoretical ventilation airflow capacity and pressure required. Fan selection is also influenced by how reserve ventilation capacity is provided either when a fan is inoperative, or during maintenance or repair of either the equipment or the power supply.

Tunnel ventilation fans usually require a large volume of air at relatively low pressure. Some fans have low efficiencies under these conditions, so the choice of a suitable fan type is often limited to double width double inlet centrifugal fans, vane axial or jet fans. Factors affecting ventilation fan selection include tunnel geometry, ventilation scheme, operation mode (reversible or not), pressure and air flow requirement. The number and size of fans should be selected by comparing several fan arrangements based on the feasibility, efficiency, and overall economy of the arrangement. Factors that should be studied include: (1) annual power cost for operation, (2) annual capital cost of equipment (usually capitalized over an assumed equipment life of 50 years for road tunnel fans), and (3) annual capital cost of the structure required to house the equipment (usually capitalized over an arbitrary structure life of 50 years). The number and size of the fans should be selected to build sufficient redundancy and flexibility into the system to meet the varying ventilation demands created by daily and seasonal traffic fluctuations and emergency conditions.

Ventilation equipment can be a major source of noise in tunnels and therefore, noise limitation is an important factor for fan selection. Acoustic treatment by means of inlet and outlet silencers and/or casings with sound-absorbing lining may be required to reduce the amount of fan noise transmitted to the tunnel and to the outside environment. The sound power level of a fan increases very rapidly with increasing tip speed. For a given volume of air, a larger and slower rotating fan will typically be quieter (but more susceptible to stall). Similarly reduction in mechanical noise can be achieved by efficient design of motor couplings, driving gear and adequate stiffening of the casing. Mounting fan equipment on insulated bases will reduce transmission of noise and vibration.

Jet Fans. Although jet fans deliver relatively small air quantities at high velocity, the momentum produced is transferred to the entire tunnel, inducing airflow in the desired direction. Jet fans are normally rated in terms of thrust rather than airflow and pressure, and can be either unidirectional or reversible. Jet fans are classified as impulse systems, since they impart a momentum to the tunnel flow, as the primary high velocity jet diffuses out. At the start-up, this thrust causes the air in the tunnel to accelerate until equilibrium is established between this force and the opposing drag forces due to viscous friction and the additional pressure losses due to tunnel portals, traffic, wind, and fire etc. In jet fan system, this thrust is distributed along the tunnel due to the installation of a series of jet fans along the tunnel.

Jet fan sizing is usually limited by space available for installation in the tunnel. Typically mounted outside of the tunnel's dynamic clearance envelope on the tunnel ceiling (above the vehicle traffic lanes), or on the tunnel walls (outside the vehicle traffic lanes), jet fans are sometimes placed in niches to minimize the height or width of the entire tunnel boundary. However, niches must be adequately sized to avoid reducing the thrust of the fans. A typical jet fan niche arrangement is provided in Figure 3.12.

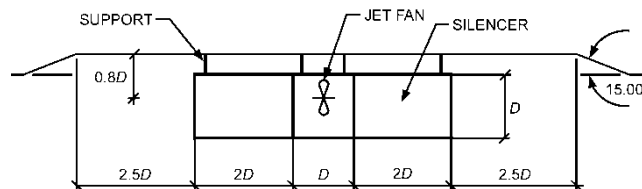


Figure 3.12: Typical jet fan arrangement in niche (ASHRAE Applications Handbook, [11])

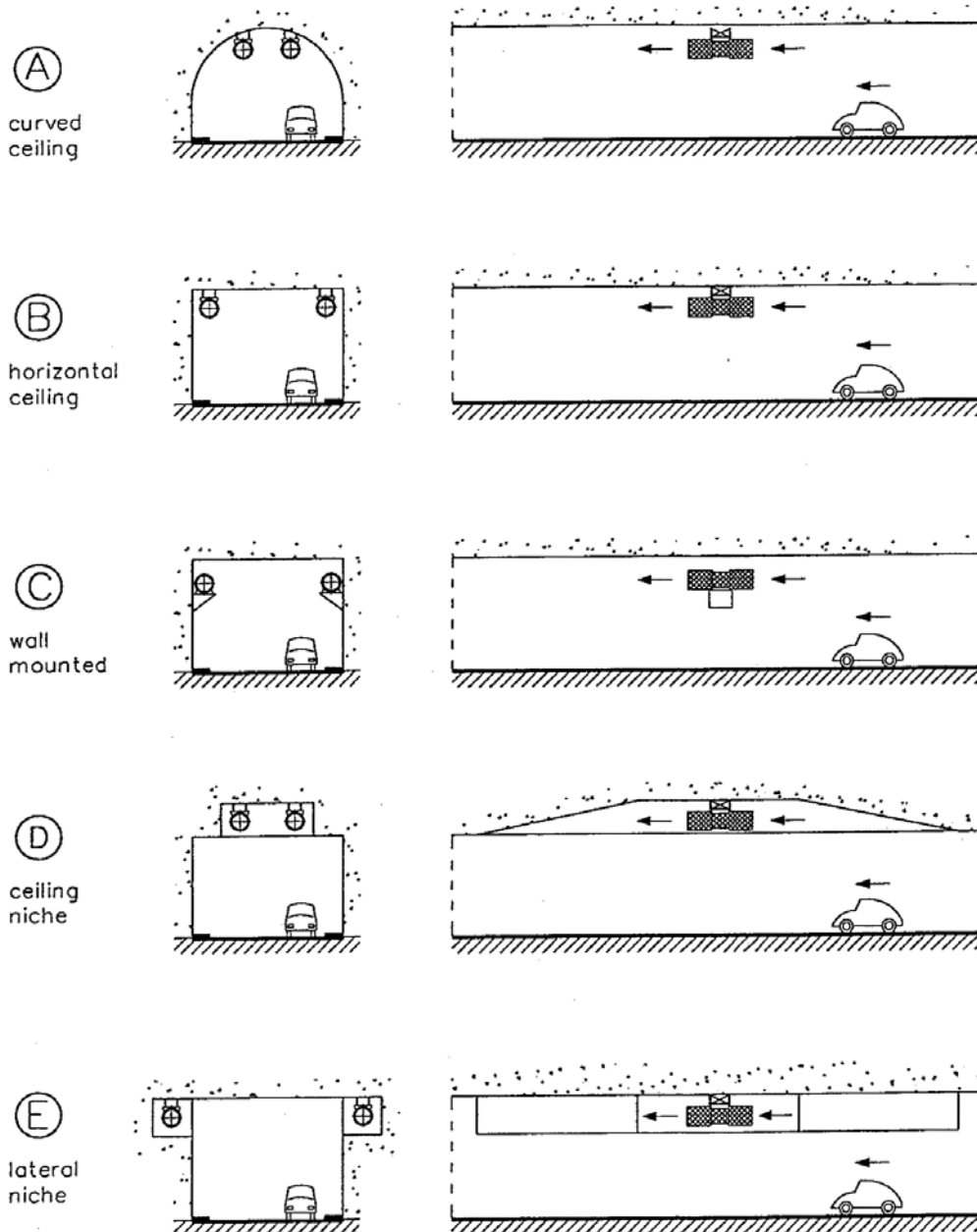


Figure 3.13: Typical jet fan installations in road tunnels

It is advisable to select the largest fan that can be fitted within the allocated space. Larger fans give a higher ratio of thrust to both capital and installation costs than smaller fans.

For the lowest operating costs, choose a low speed and/or low pitch angle fan. The ratio of power to thrust is directly related to the fan outlet velocity so for any given thrust requirements, the higher the velocity, the higher the power consumptions and higher noise levels. However, reducing the thrust for a given fan size increases the number of fans needed and hence the capital costs.

For jet fans, additional sound-absorbent material in fan casing, and inlet and outlet silencers should be considered. Any increased head loss caused by a silencer, in some designs, can only be compensated for

by increased fan energy consumption and hence higher potential noise levels. The design should ensure that during fire emergencies, noise levels in the tunnel do not exceed the levels defined in NFPA 502 and do not interfere with the use of emergency communication system and operation of first responders. As a note, reversible jet fans are marginally less efficient and slightly noisier than uni-directional fans.

Jet fans being installed in the tunnel are subject to high temperatures during the fire events. In case of a large fire (such as 300 MW [1020 MBtu/hr]) jet fans could be damaged over a distance of up to 300 to 500 m (984 to 1640 ft) downstream of the fire, which should be accounted for in the design. This distance depends on tunnel geometry, fire size and its spread, fan design, ventilation conditions and etc. and should be analyzed using fire simulations tools. The fan damage can be significantly reduced if a fixed fire suppression system is installed in the tunnel. Jet fans are typically specified to withstand 250°C (482°F) for one hour. Some designs require jet fans to be designed for 400°C (752°F) for up to two hours and not to fall down during the firefighting phase.

Table 3.4: Maximum air temperatures experienced at ventilation fans during Memorial Tunnel Fire Ventilation Test Program [11]

Nominal FHRR, MW (MBtu/h)	Temperature at Central Fans, ^a °C (°F)	Temperature at Jet Fans, ^b °C (°F)
20 (68)	107 (225)	232 (450)
50 (170)	124 (255)	371 (700)
100 (340)	163 (325)	677 (1250)
FHRR = Fire heat release rate ^a Central fans located 700 ft (213 m) from fire site. ^b Jet fans located 170 ft (52 m) downstream of fire site.		

British Standards provided data on distances over which jet fans were assumed to be destroyed by the fire (see Table 3.5) [43]. This table could be used as an example, but does not replace the calculations required.

Table 3.5: Distances over which jet fans are assumed to be destroyed by a tunnel fire (BD 78/99) [43]

Fire size, MW (MBtu/h)	Distance upstream of fire, m (ft)	Distance downstream of fire, m (ft)
5 (17)		
20 (68)	10 (32.8)	40 (131.2)
50 (171)	20 (65.6)	80 (262.5)
100 (341)	30 (98.4)	120 (393.7)

French guidance provides smoke temperatures at various distances (CETU, 2003). This is reproduced in Table 3.6, which could be used as an example, but does not replace the calculations needed.

Table 3.6: Smoke temperatures near the ceiling, with airflow close to critical velocity (CETU, 2003) [43]

Downstream distance	10m (33 ft)	100m (330 ft)	200m (656 ft)	400m (1,312 ft)
Light vehicle fire	250°C (482 F)	80°C	40°C	30°C
HGV fire	700°C (1,292 F)	250°C (482 F)	120°C (248 F)	60°C
Tanker fire	>1000°C (>1,832 F)	400°C (752 F)	200°C (392 F)	100°C (212 F)

The following should be noted:

- Jet Fans are not as efficient as axial fans operating in a ducted system. However, low capital cost and simplicity of installation and maintenance may justify their use.
- Fan performance is highly impacted by fan installation, spacing between fans, signs and other equipment located in the air stream.
- Fans should be provided with anti-vibration mounting which should be fail safe. Safety chain installation is a good practice to secure fans.
- Water entering the jet fans from any source needs to drain out.
- Sealed-for-life bearings should be considered.
- Designs should consider redundancy of jet fans due to loss of power or maintenance related issues.

Saccardo Nozzle fans. Injection longitudinal ventilation uses externally located supply fans to inject air into the tunnel through a high-velocity Saccardo nozzle. The Saccardo nozzle functions on the principle that a high-velocity air jet injected at a small angle to the tunnel axis can induce a high-volume

longitudinal airflow in the tunnel. The amount of induced flow depends primarily on the nozzle area, discharge velocity and angle of the nozzle, as well as downstream air resistances. Air velocities discharged into the tunnel through Saccardo nozzles are similar to the jet fans discharge velocities. Saccardo fans (injectors) are located outside the tunnel in the ventilation buildings making them ideal in tightly spaced tunnels and easy for maintenance. Fans are not subject to high temperature exposure. Fans can be located horizontally or vertically depending on the vent building design. Fresh air intake for the supply fans should meet security requirements. Special considerations should be given to the noise developed by the Saccardo fans due to high velocity pressure requirements.

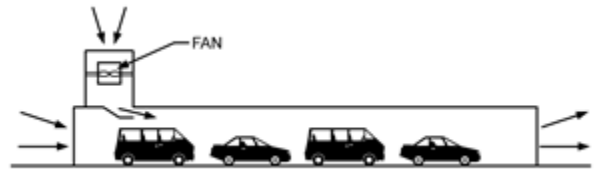


Figure 3.14: Longitudinal ventilation with Saccardo nozzle

Consideration should also be given to the geometry of the injector aerodynamic design to reduce pressure losses.

Fans used in transverse ventilation schemes are located in the vent buildings and can be either centrifugal or axial flow and installed horizontally or vertically.

The type of fan is determined by the required airflow and pressure for fire emergency and normal operating conditions and the available space in the tunnel configuration. Fans used in tunnel ventilation should be constructed to withstand the maximum pressure and temperature anticipated. Flow reversibility is frequently required in tunnel ventilation systems. Most tunnel ventilation fans are driven by electric motors. The fan motor selection is based on the full load horsepower requirements, fan speed and the starting characteristics.

Several fans installed in parallel typically serve a single ventilation duct due to high airflow requirements and relatively low pressure needed. Fans operating in parallel should be of equal size and have identical performance curves. Actual airflow capacities can be determined by plotting fan performance and system curves on the same pressure-volume diagram. If airflow is regulated by speed control, all fans should operate at the same speed. If airflow is regulated by dampers or by inlet vane controls, all dampers or inlet vanes should be set at the same angle. For axial-flow fans, blades on all fans should be set at the same pitch or stagger angle.

Fans selected for parallel operation may be required to operate in a particular region of their performance curves, so that airflow capacity is not transferred back and forth between fans. This is done by selecting a fan size and speed such that the duty point total pressure, no matter how many fans are operating, falls below the minimum total pressure characterized by the bottom of the stall dip or unstable performance range.

Fans in the exhaust air duct are exposed to a mixture of very hot air from the immediate surroundings of the fire, which could be diluted by cooler air further away from the fire. The fresh air/smoke mixture is also subject to thermal exchange with the duct walls before reaching the fans. This mixture of hot and

cooler air then travels in the duct and gets cooled down further (see Table 3.4). A fire resistance of the fans to 250°C (482°F) could be considered sufficient for most fire events, but needs to be checked for the design fire scenario. There can be residual thermal expansion of the gases passing through the fans. This phenomenon must be taken into account when establishing the thermal resistance criteria and capacities of the extraction fans. The thermal resistance of the fans must ensure that the extraction of the hot smoke is possible with any configuration. When the fire location is relatively close to the extraction point, the exhaust temperature may be significantly higher than 250°C. This was the reason for increasing the thermal resistance of exhaust fans in Austria and Germany to 400°C for 90 minutes, and in France to 400°C for 120 minutes depending on the location of the fans relative to the tunnel traffic [16].

Centrifugal fans can have either single or double inlet impellers with radial, forward curve or backward curve blades. The most commonly used is the double width double inlet backward curve fan because of its relatively smaller space requirement, greater efficiency and non-overloading characteristics at selected speed. All centrifugal fans due to their designs require a larger amount of space than axial fans of the same duty. Some advantages over axial fans are that centrifugal fans are more efficient and less noisy and provide higher pressure capability. The performance of centrifugal fans is effected by:

- variations in speed
- outlet damper control
- variable inlet guide vanes

Axial fans can be vane axial or tube axial with single stage or multistage construction. These fans have the ability to handle extremely large quantities of air and are frequently used in tunnel ventilation design. Axial fans can be mounted horizontally or vertically in ventilating shafts thereby reducing space requirements relative to centrifugal fans. Axial flow fans are often used in ventilation of major road tunnels. Capacities are often in excess of 100 m³/s. The large diameter fans are located in fan rooms with connecting shafts supplying and extracting air to or from the tunnel section or its full length depending on ventilation system design.

An axial flow fan is one in which air passes between aerodynamically shaped blades to enter and exit axially to the direction of rotation. Reverse flow may be achieved by reversing the direction of the rotation of the motor.

System effects should be considered in the pressure loss calculations when designing the fan and duct configuration for all fan types and for all ventilation schemes, particularly the fan inlet and outlet conditions.

Tunnel ventilation fans can have multiple speeds controlled by adjustable speed drives, or two- or three-speed motors or multiple motor drives. Axial fans can be produced with controllable blade pitch in motion (variable-pitch blades) for control of airflow and thrust. Fans can be aerodynamically stabilized by means of anti-stall ring which introduces on each side of the impeller, providing stable flow conditions and continuously rising fan characteristics in both flow directions. When in the stall region, the separated and highly turbulent flow is removed from the main flow annulus and entered into the stabilized peripheral ring-shaped duct just upstream of the impeller blades.

NFPA 502 requires that “tunnel ventilation fans that are to be used in a fire emergency shall be capable of achieving full rotational speed from a standstill within 60 seconds. Reversible fans shall be capable of completing full rotational reversal within 90 seconds [1].” The emergency ventilation system should be capable of reaching full operational mode within a maximum of 180 seconds of activation. Fans could be activated sequentially based on fire zones. Fan motors typically have adjustable speed drives, soft starters, or direct on line motor starters. The selection of the motor controller will affect the sequencing times, startup times, inrush current, motor durability, generator sizing, flexibility of the system, efficiency, etc.

3.4 EFFECTS OF VENTILATION ON TUNNEL FIRES AND FIRE SIZES

Ventilation has an influence on fire development, but it does not always conform to expectations; this influence depends on the location of the fire origin and the sufficiency of air [44].

1. Due to increased ventilation, the development of a car fire can be slowed if the fire ignites at the front of the car. This is in contrast to the accepted view of supposed accelerated development due to ventilation.
2. The influence of increased ventilation on the observed fire behavior depends on the ignition location. Note that the majority of fires begin in the engine compartment (i.e. at the front).
3. Under the influence of a high ventilation velocity, fire development accelerates for a covered load at a rate 2-3 times faster than an uncovered load. The fire size is also 20-50% higher due to a high ventilation speed.

Ventilation could cause flame deflection, which leads to the chance that the fire might spread to other vehicles and threaten the integrity of the tunnel structure on a larger surface, assuming the ventilation cooling effect and reduction in radiation at the source are insignificant. In most cases, mechanical ventilation will lead to complete combustion (the fire to burn fully). Thus, the total duration of the fire (if not timely extinguished) will be limited to the time to complete combustion. It is understood that there could be a negative effect of ventilation as forced ventilation may cause significant flame deflection and fire spread by convection.

The increase in peak HRR and fire growth rate, due to increased velocity, is the result of more effective heat transfer from the flames to the fuel surface. In some cases, it results in a more effective transport of oxygen into the fuel bed, which enhances the mixing of oxygen and fuel. The oxygen unlimited larger pool fires (in wide tunnels) dominated by radiation heat flux from the flames are less affected by ventilation than small fires dominated by convective heat transfer from the flame volume.

Starting a ventilation system when the fire has been ongoing for some time in a tunnel with high vehicle density and oxygen deficiency may offer some risk due to supplying oxygen to the fire and possible fire spread. However, as ventilation cannot reach its full operating mode immediately, the risk may be justified.

Influence of ventilation rate on fire growth rate from the Benelux and Runehamar fire is presented in Table 3.7.

Table 3.7: Influence of ventilation rate on fire growth rate [45]

Ventilation Rate	Growth Rate
Less than 1 m/s (200 fpm)	About 5 MW/min (17 MBtu/hr/min)
About 3 m/s (600 fpm)	About 15 MW/min (51 MBtu/hr/min)
About 6 m/s (1200 fpm)	About 10 MW/min (34 MBtu/hr/min)

Tests indicated that the fastest fire growth may occur at about 3 m/s airflow velocities. Both higher and lower ventilation rates may result in slower growth fires. These observations were made on the basis of only a few experiments. More research is needed to confirm (or otherwise) the validity of these conclusions [45].

The flame spread rate in a tunnel fire is proportional to the ventilation velocity. However, there is some evidence of the decrease effect under highly ventilated conditions (the blow-off effect).

The ventilation conditions are important for the combustion gases production. In an under-ventilated fire situation the yield of major toxicants is greater, compared to well-ventilated conditions. The main effects of longitudinal ventilation are an increase of the growth rate of the fire and an increased dilution of gases. Under high ventilation rate conditions only downstream flame exists, while under low ventilation conditions both upstream and downstream flames exist. Under low ventilation conditions, the total flame length increases with decreasing ventilation velocity despite that the downstream flame length is approximately invariant. The maximum total flame length is obtained when there is no ventilation in the tunnel and it is approximately twice the downstream flame length in tunnel fires under high ventilation.

3.5 FIRE SMOKE STRATIFICATION AND LENGTH OF STRATIFICATION AND ITS IMPACT ON EMERGENCY VENTILATION

This section applies to cases where stratification of smoke exists. During fires with a significant heat generation rate, the hot smoke flows upward due to the buoyancy force and impinges on the tunnel ceiling and then flows along the tunnel ceiling longitudinally. A substantially smoke-free layer is formed below the smoke layer. As the smoke travels along the ceiling, the smoke temperature decreases rapidly with distance mainly due to heat loss to the tunnel structure. This indicates that the thermal pressure also decreases with distance [30]. Therefore, smoke stratification becomes more and more difficult to maintain as the distance from the fire increases. Thermal pressure tends to maintain smoke stratification but the inertia force tends to destroy it. Due to a complex process of mass and heat exchange, the smoke is gradually cooled and mixed with the air. After a period of time, both upstream and downstream sections of tunnel can be completely filled with smoke. Therefore, stratification is a temporary phenomenon unless it is maintained by appropriate ventilation including extraction from the ceiling and control of longitudinal air velocity.

Non-dimensional parameters that describe the balance between these two forces are the Richardson number (Ri) and local Froude number (Fr); both of them correlate the buoyancy force with the inertia force and indicate the stability of the smoke layer, but in an inverse relationship to each other. As the Richardson number increases, the smoke stratification becomes more stable. When $Fr \leq 0.9$, there is severe stratification in which hot combustion products travel along the ceiling. The gas temperature near the floor is essentially ambient. This region consists of buoyancy dominated temperature stratification and could be used for egress. [30]

When the air temperature at the tunnel ceiling is significantly higher than at the level where the fire starts, the upward movement of the smoke plume may cease due to the lack of buoyancy and additional stratification may occur.

The fire smoke layer and stratification may depend on the fire size (heat release rate), tunnel type, tunnel geometry, and longitudinal ventilation flow. When the longitudinal ventilation is gradually increased, the stratified layer may gradually dissolve. The need to maintain the smoke stratification upstream to the fire leads to the concept of critical velocity in emergency ventilation. In addition, recent research has provided the results on the length and duration of smoke stratification.

In tunnels with natural ventilation and low air velocities (0 -1 m/s [0 – 200 fpm]) the stratification of the smoke is usually in the vicinity of the fire source. The backlayering length of the smoke is relatively long and in some cases, the smoke travels nearly uniformly in both directions. When the velocity increases and is close to about 1 m/s (200 fpm), the smoke upstream of the fire is inhibited by the ventilation and prevented from spreading further. The length of this backlayering smoke layer from the fire site could be in the order of 25 times the tunnel height.

At longitudinal air velocities of 1 to 3 m/s (200 to 600 fpm), the stratification in the vicinity of the fire is strongly affected by the air velocity, especially at the higher velocities. The backlayering length could vary. For a ventilation velocity slightly lower than the critical velocity, smoke backlayering and good stratification exist upstream of the fire. However, the smoke stratification downstream becomes worse.

At high air velocities, over 3 m/s (600 fpm), the stratification of the smoke downstream usually disappears and no backlayering exists upstream of the fire, which can be observed in tunnels with longitudinal ventilation. Cold air at high velocities could bypass the fire plume without mixing with smoke.

The back-layering length, L_b (m), is defined as the length of the smoke back-layering upstream of the fire when the ventilation velocity is lower than the critical velocity.

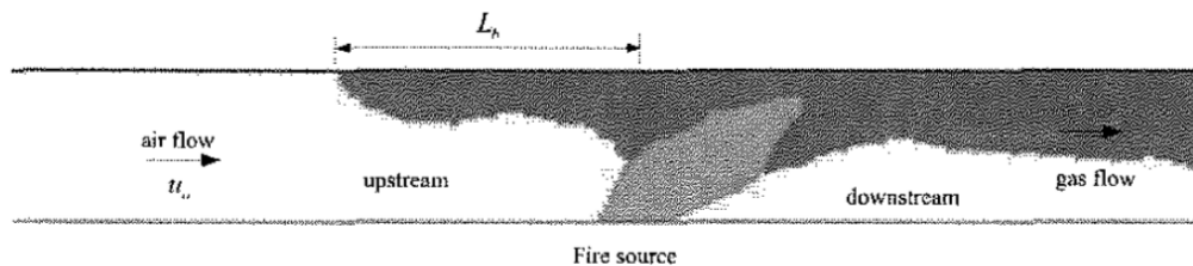


Figure 3.15: Schematic of backlayering of smoke in a tunnel fire [30]

In a longitudinally ventilated tunnel, a fresh air flow with a velocity not lower than the critical velocity at the designed HRR is created to prevent smoke backlayering and therefore, the tunnel is free of smoke upstream of the fire site.

However, smoke stratification downstream of the fire may not persist as the ventilation velocity is too high. For this reason, a new term, "confinement velocity", has been introduced. This is the velocity needed to prevent back-layering at a certain position, that is, to prevent spreading further upstream. The "confinement velocity" is defined as the longitudinal velocity as induced by the extraction ventilation system which is necessary to prevent smoke layer development after the last exhaust vent has been activated. The reason for using such a velocity is the attempt to control back-layering and, at the same time, to preserve certain stratification.

The back-layering length increases with the HRR for low HRRs and is nearly independent of HRR and dependent only on the ventilation velocity at higher HRRs. A small change in velocity will result in a greater change in back-layering length.

Smoke extraction ventilation suggests that smoke flows (plume flow) arising from a fire should be directly exhausted by the exhaust ventilation system in the vicinity of the fire.

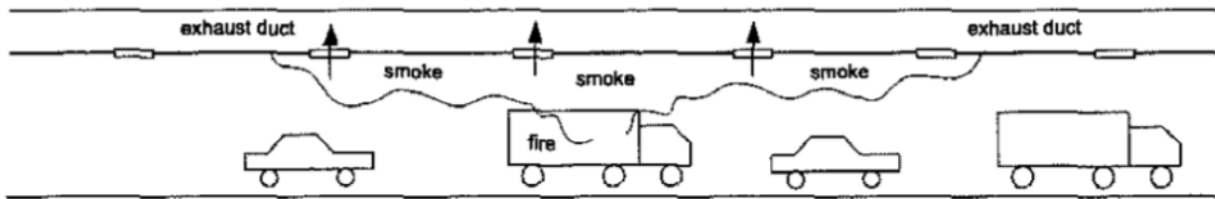


Figure 3.16: Point extraction ventilation [30]

The exhaust ventilation system should be sized to extract the smoke flow rate, which depends on the fire HRR, gas temperature, tunnel geometry, and ventilation. When the smoke layer is relatively shallow, a high extract rate at any point may lead to 'plug-holing', where some air is extracted from below the smoke layer as opposed to the smoke itself. The traditional method always tries to avoid plug-holing, that is, the smoke flow is extracted slowly with multiple extracted points. The extract rate from one point should not exceed:

$$M = \beta [g(h - z)^5 (T_s - T_o) T_o]^{1/2} / T_s \quad [30]$$

Where

M – extract rate, kg/s;

g – acceleration due to gravity 9.81 m/s²;

β – is a numerical factor of 2 where the extract point is near the wall and 2.8 where the extract point is distant from the wall (limited experimental data);

h – is the tunnel height;

z – is the height of the layer interface (smoke-free height);

T_o – is the absolute ambient temperature, (K);

T_s – is the average (absolute) smoke layer temperature, (K).

If the two extract openings are close together, the flow around them will basically be the same as if they were one point. NFPA 92 provides guidance for the minimum separation between extract points.

Incoming airflows with a sufficiently large ventilation velocity should be supplied from both sides of the smoke extraction systems to successfully prevent smoke from spreading further. In most practical applications, the main objective is to only partly remove the smoke flow. As the smoke flow cannot be completely controlled within a small region between vents and the fire source, it spreads to a much larger region.

In case of a fire, the location of the fire is determined by the fire detection system and then the extraction vent or vents near the fire site can be opened to extract smoke flows (see Figure 3.9 in Section 3.1). The number of open vents will depend on the fire size and the designed volume flow rate for each vent. Meanwhile, the other vents should close or remain closed.

Critical or at least confinement velocities to both sides of extraction zone should be maintained. Some international guidelines recommend those velocities to be 1.5 – 2 m/s (300 – 400 fpm) [39].

According to the law of mass conservation, the critical extraction mass flow rate of the extraction ventilation required for confining the smoke to a small region between the fire and the extraction vent, \dot{m}_{ex} , could approximately be estimated using:

$$\dot{m}_{ex} = 2\rho_o u_c A$$

Where: ρ_o – is the outside air density;

u_c – is the critical (or at least confinement) velocity;

A – is the tunnel cross section area.

The number of and spacing between exhaust openings for a single point exhaust system depends on several factors:

- The accuracy of the fire detection system and the fire location relative to the exhaust openings. At least two, or preferably three or more openings, should be opened to effectively extract smoke;
- The activation time of the ventilation system. The smoke may have spread over 1 km or more from the fire site depending on the fire detection and ventilation system operation design;
- The presence of a longitudinal ventilation system and control system (including air velocity sensors in the tunnel) to control air velocities to both sides of the extraction openings;
- Zone of tenability, tunnel geometry, egress features, etc.

As the application of the tenability criteria at the perimeter of a fire is impractical and the zone of tenability should be defined to apply outside a boundary away from the perimeter of the fire, it is practical to consider a smoke extraction zone of not less than 90 m (300 ft) long with at least 3 exhaust openings spaced at least 30 m (100 ft) apart.

Note that smoke stratification may not happen when the fire heat generation rate is insignificant and the smoke production rate is significant. In such situations, tenability can be lost due to the ‘non-stratified smoke’. This could be especially dangerous before fire life safety systems are activated. As the heat generation rate is low, the smoke temperature would be close to ambient, while smoke could be

very toxic and impair visibility. Such smoke could be managed by the tunnel ventilation system with low critical velocity numbers and smoke management could be achieved with airflow driven in the desired direction. The tunnel ventilation system shall be evaluated for this scenario.

4 TUNNEL FIRE DETECTION AND VENTILATION IMPACT

The detection of a fire is of paramount importance since not detecting an event could mean the loss of precious time to save lives and property. Timely fire detection allows for timely evacuation, rescue, control of tenable environment and firefighting. Fire detection is conducted based on exceeding threshold values for a prescribed duration. Fire detection should provide a means of detecting a fire in all parts of a tunnel and ancillary areas, provide a means of activating an alarm for evacuation and activating other fire safety measures such as the tunnel ventilation system, and send an alarm to the fire services.

NFPA 502 requires to detect, identify and to locate fires in all tunnels over 800 ft (240 m) long and in shorter tunnels with a high volume of traffic or high level of risk [1]. The NFPA 502 Standard allows for manual means to identify and locate fires within tunnels with no fixed firefighting systems that are equipped with CCTV cameras with incident management software and a warning notification system. At least two means of identifying and locating fires are required.

Automatic fire detection is required for tunnels equipped with a fixed firefighting system. With no operator supervision (unmanned tunnels), an automatic fire detection system is needed for tunnels over 1000 ft.

The key objective of the automatic tunnel fire detection and warning systems is to provide prompt, accurate, and reliable fire detection while preventing nuisance alarms. Prompt and accurate fire detection will result in timely activation of tunnel ventilation system in the predetermine mode of operation to maintain tenable environment for evacuees. The goal should be to detect a fire of 5 MW (17 MBtu/hr) or less within 60 - 90 seconds in a testing environment with 3 m/s (600 fpm) of air velocity. It should accurately detect the fire within a fire zone which defines the activation limits of the ventilation and fixed fire suppression system for a particular length of the tunnel. Quicker detection of a smaller tunnel fire in a shorter time has been proven possible. Automatic activation of the ventilation and firefighting systems could be considered but is not currently required by the NFPA 502 Standard due to concerns related to the reliability of the tunnel fire detection systems [1].

Depending on the nature of the fire, any of the following can start developing first: smoke, flame, or heat. Consequently, multi-sensor alarm systems are better suited for automatic control.

Induced airflow in road tunnels may reduce air temperature, surface temperature, dilute smoke concentration and deflect flames, which impacts the performance of the tunnel fire detection devices. This may result in delayed fire detection, detection of the wrong fire zone, or inability to detect fire. In relatively short tunnels, just before the fire event occurs, the mechanical ventilation seldom operates at high speed and induced airflow is primarily driven by the piston effect and other natural ventilation sources. Hence, the impact of mechanical tunnel ventilation on the fire detection systems' performance could be of interest for very long tunnels only. However, the impact of natural ventilation has to be analyzed when selecting the fire detection device. In addition, the tunnel slope may also have some impact on the accuracy of detecting the fire zone.

Additional Information on tunnel fire detection and warning systems design can be found in Appendix A.

5 TUNNEL FIXED FIREFIGHTING SYSTEMS AND VENTILATION IMPACT

Active tunnel fire protection systems can be classified as fixed systems and standpipe systems. Fixed fire protection systems used in road tunnels are fixed, water-based firefighting systems. Standpipe systems are used in the U.S. primarily by firefighters to suppress and extinguish fires.

Fixed water-based firefighting systems are categorized based on their performance objectives as:

- fire suppression systems with the goal to reduce the fire HRR by sufficient application of water; Consideration should be given to the water flows from those systems – water density.
- fire control systems with the goal to stop or significantly slow the fire growth rate
- volume cooling systems with the goal to provide substantial cooling of the products of combustion but not intended to reduce fire HRR
- surface cooling systems with the goal of protecting the main tunnel structural elements but not intended to reduce fire HRR

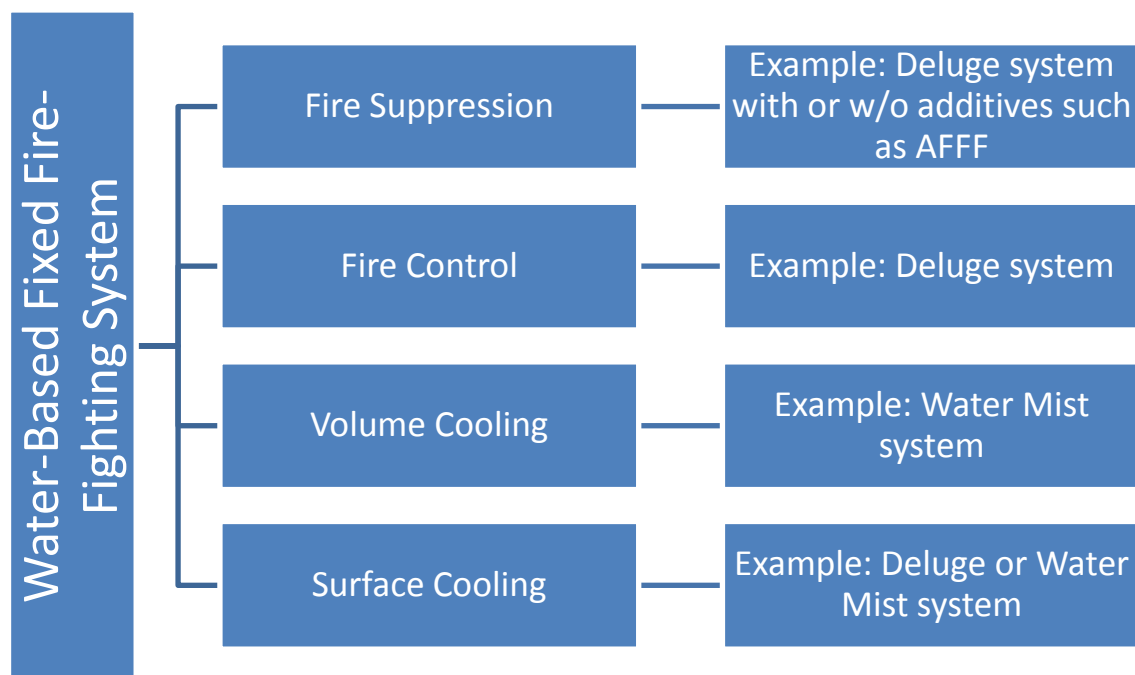


Figure 5.1: Effects of water based fixed firefighting systems

Additional information on tunnel fixed firefighting systems can be found in Appendix B.

Activation of the deluge system may lead to less tenable conditions in the immediate vicinity of the deluge due to some layer cooling and de-stratification. The undesirable consequences of water based fixed firefighting system activation, such as smoke de-stratification, increased humidity, and decreased visibility are typically outweighed by their positive outcomes such as fire growth rate control, containment of fire spread, and reduced temperatures. Table 5.1 discusses the impact of the fixed firefighting system on tunnel fire safety and its interaction with different tunnel ventilation systems.

Table 5.1: Impact of fixed fire suppression system on tunnel fire safety

Advantages of FFSS	Challenges of FFSS
<u>General</u>	
A FFSS is designed to react on an early stage of the fire. Controls fire by not allowing it to further grow, or grow slowly, or extinguishing a small fire.	Reduced visibility especially on an early stage when people evacuate. When the sprinkler system is activated on an already large fire, smoke stratification will be destroyed and a large amount of water will be evaporated and, thus, the visibility will be further diminished.
Protection of tunnel users and structure. Duration of the fire can be limited and the structure of the tunnel will be subjected to less harsh conditions.	Incomplete combustion creates smoke, gases and steam. Studies needed on critical time to activate the FFSS system to protect tunnel structures.
Support rescue and firefighting: help rescue and firefighters to reach the fire source.	Creates slippery environment when water applies. Malfunctioning of the system with accidental water release may create panic which may lead to an accident.
<u>When FFSS applies with transverse ventilation based on smoke extraction (including single point extraction)</u>	
Reduced fire size; also see general	Destroys stratification of hot air which makes ceiling extraction inefficient and makes evacuation more difficult especially in a fire suppression zone.
Reduced fire duration	Increases in mass of air / water mixture and mass of smoke due to incomplete combustion which results in increased ventilation rate needed for extraction system.
<u>When FFSS applies with longitudinal ventilation – unidirectional tunnel with manageable traffic</u>	
Reduced fire size may result in reduced ventilation rate	Increases in mass of air / water mixture and mass of smoke due to incomplete combustion – which might increase required ventilation rate.
Cools environment and protects fan units from high temperature	Creates water curtains which impact ventilation design by increasing pressure (thrust) needed for ventilation to overcome.
See general	Ventilation blows the FFSS substances away from fire which may increase number of FFSS zones for activation depending on weight of water particles and pressure.
<u>Longitudinal ventilation – unidirectional tunnel with unmanageable traffic or bidirectional tunnel</u>	
Protects tunnel structure and reduces fire size	Destroys stratification making evacuation difficult to both sides of the fire especially in a fire suppression zone. Traffic control for low traffic tunnels is imperative.

Research projects are investigating to what extent an active fire protection system can limit the maximum heat release rate of a fire and whether an active fire protection system combined with ventilation offers equal or better life safety than ventilation alone. The projects are also investigating how to specify design or performance test criteria for active tunnel fire protection systems.

5.1 INTERACTION BETWEEN WATER BASED FIXED FIRE SUPPRESSION AND TUNNEL VENTILATION SYSTEMS

The tunnel ventilation system is still the main tunnel fire life safety system to control smoke and provide a tenable environment for evacuation. Table 5.2 illustrates that there are a number of common benefits from ventilation and FFSS which can support each other in cooling down the tunnel environment and supporting firefighting procedures. However, there are several expected conflicts noted between the two systems, such as fire growth, fire spread, visibility and tenability.

Table 5.2: Expectations from tunnel ventilation and fixed fire suppression systems

Tunnel Ventilation		Fixed Fire Suppression	
Expected benefits	Expected Concerns	Expected benefits	Expected Concerns
Controls smoke and other gases	Supplies oxygen to fire and increases the fire growth	Slows down the fire growth, reduces fire size and overall smoke production. Smoke production could be significantly reduced by starting FFSS at incipient fire development stage.	Reduces visibility and thus negatively impacts the ability to evacuate
Provides tenable environment for evacuation, including visibility	Supports spreading fire further impacting other vehicles	Prevents spreading of fire further impacting other vehicles	Destroys stratification of hot air and smoke and may disrupt ventilation system operation
Cools down the tunnel environment		Cools down the tunnel environment. Cooling effect of FFSS on critical velocity and ventilation requirements	Increased humidity and its impact on tenability and on fan design
Supports firefighting procedures		Supports firefighting procedures	Produces toxic smoke due to incomplete combustion
		Protects assets and possibly structural protection	Develops slippery hazard for evacuation

Longitudinal Ventilation

The impact on the fixed fire suppression system largely depends on the type of tunnel ventilation and on the magnitude of the longitudinal airflow along the tunnel. With longitudinal ventilation, smoke is pushed through the tunnel toward the portal at air velocities not less than “critical velocity” in order to prevent the smoke from backlayering. NFPA 502 and other standards allow for a maximum air velocity in a tunnel of 12 m/s (2200 fpm) [1]. Ventilation systems are designed for significantly smaller critical air velocities, but in combination with wind, other natural factors, and the traffic pattern, the resultant air velocities may reach those velocities.

At high longitudinal air velocities, light water mist droplets will most likely be blown away, while heavy deluge water droplets will be displaced. As of today, water mist systems have been tested at significantly lower longitudinal air velocities than expected in an emergency scenario, not exceeding 5 m/s (1000 fpm). Field tests performed by water mist companies in San Pedro de Anes (Spain) [26] indicated that a low longitudinal air velocity will have a minor impact on FFFS performance.

Experimental model scale tests performed in Sweden concluded that fully automatic FFFS are only suitable for tunnels with low velocities and recommended that automatic FFFS be used in tunnels with transverse ventilation or in bi-directional tunnels rather than in longitudinally ventilated tunnels with high velocities [27]. The deluge system, using much heavier (larger) water droplets, may be considered for operation in high longitudinal air velocities once it is proven that it provides a similar or a higher level of safety. The deluge system with and without 3% AFFF additives was tested in different relatively low longitudinal air velocities as shown in Figure 5.2 and while some displacement of heavy water droplets was observed, displacement of the zone covered by the fixed fire suppression system was insignificant [50]. However, we can expect it to be more significant at high air velocities and with lighter water particles.

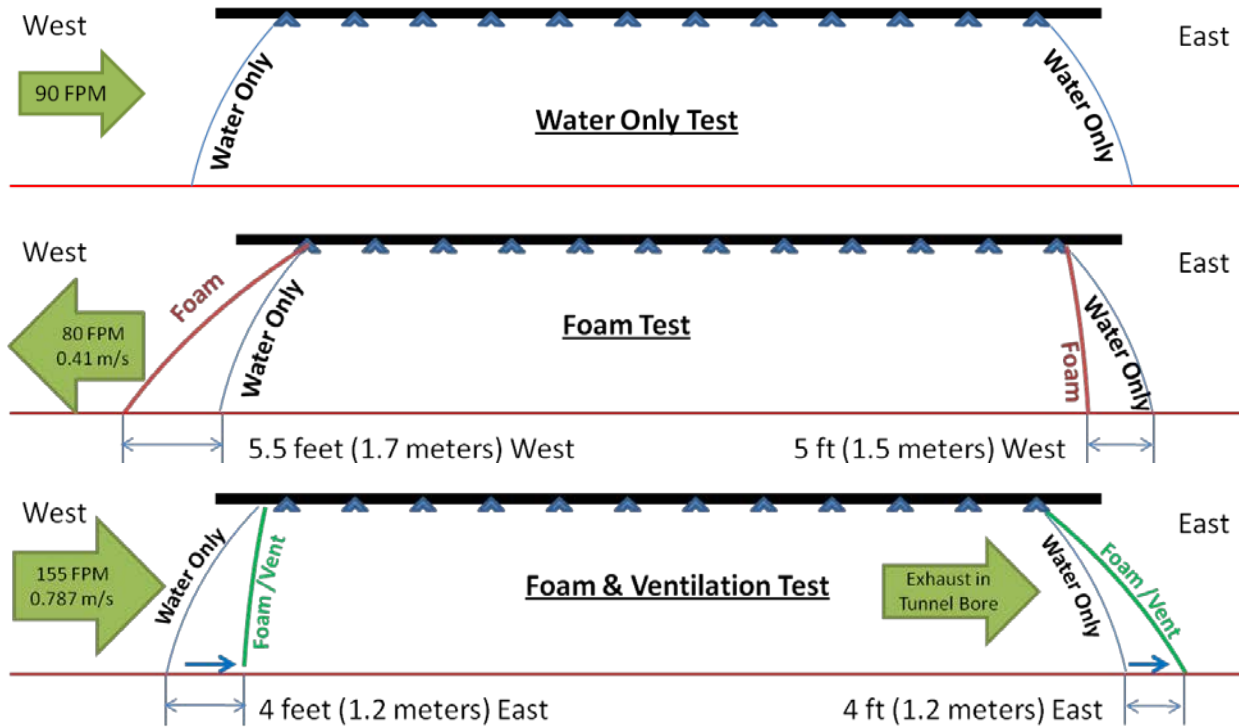


Figure 5.2: Displacement of FFSS water particles as the result of longitudinal air velocity [50]

The design of the fixed firefighting systems should be fully coordinated with the tunnel ventilation system design as ventilation equipment, such as the jet fans or the fan/supply openings, may have a significant impact on the performance of the water droplets of the sprinkler heads.

Jet fans, lights, signage, and other possible obstructions should be taken into account when installing nozzles. Nozzles are normally installed under the tunnel ceiling and/or at the upper part of the walls, pointing downwards or at the center of the tunnel and disperse into the protected area. Nozzles should be arranged such that vehicles will not reduce their efficiency by blocking the spray to a critical extent. This applies especially to systems having nozzles installed on the walls or with just one row of nozzles along the tunnel ceiling. This may lead to local variations of nozzle spacing or lowering the installation position of the nozzles below obstructions, such as jet fans. Variations in tunnel geometry, e.g. emergency stop lanes or other areas where vehicles potentially can enter, should also be taken into account. It is advisable to locate sprinkler heads above and under the jet fans and locate the nearest sprinkler head further away from the jet fan discharge.

While it may take about 30 seconds to activate a wet sprinkler system, it may take 3 to 4 minutes to fully implement the ventilation mode due to inertia and electrical loads. This means that the sprinkler system can be activated in a relatively calm environment before ventilation is at full speed. This allows for a faster wet FFSS system to be activated over the incident zone. However, once the ventilation mode is in full effect, the sprinkler activation zones may need to be switched to account for a blow-away effect from the longitudinal ventilation. This could require deactivation of one downstream zone and activation of an upstream zone under full system pressure. The fire zone would likely stay activated throughout the process.

System activation, by opening the emergency control valve and deactivation by closing the valve, is a critical component of controlling the deluge system for optimum effectiveness. Recent technological advances have made it possible to activate and deactivate the deluge system with one simple ball valve and/or a remotely controlled solenoid valve. Valve operation utilizes standpipe water pressure fed to the back side of the valve. Under no circumstance should there be a complete deactivation of the deluge sprinkler system until either the fire is extinguished or managed by the fire department.

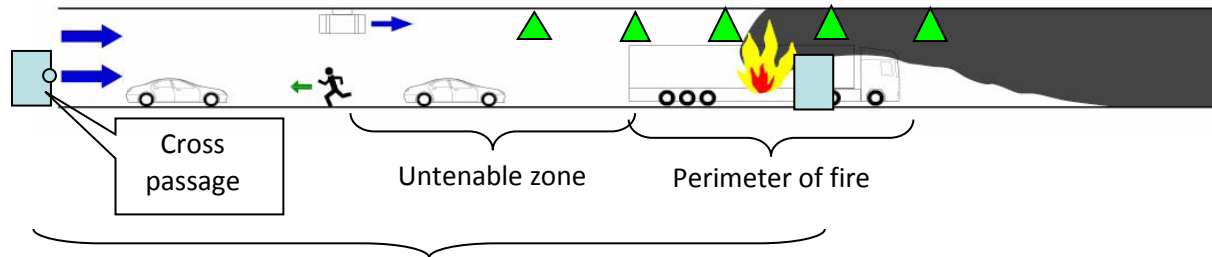


Figure 5.3: Longitudinal ventilation with fixed fire suppression system

Tests in I-90 tunnels in Seattle demonstrated that with a longitudinal air velocity, the water/foam droplets enter a shielded volume and can reduce the fire size inside the enclosure [49]. While the fixed fire suppression system was unable to extinguish a 2 MW (7 MBtu/hr) shielded fire inside the van during the tests, the tunnel air temperature around the burning van was reduced preventing the fire from spreading. It was an important observation that the temperatures inside the van were also reduced as water droplets blown by the tunnel airflow enter the van through the open windows and evaporate, lowering the energy inside of the van. The suppression system cools the outside of the van and the surrounding air. This leads to convection of the hot air (inside the van) to the cooler environment outside of the van. Ventilation controlled smoke movement kept one side of the fire completely tenable when stratification was destroyed by the fixed fire suppression system [49].

In the absence of any ventilation, the activation of a fixed fire suppression system may reduce visibility as shown in Figure 5.4. In these tests, stratified smoke was allowed to build up along the ceiling and therefore, if a fixed fire suppression system is activated quickly, the loss in visibility may not be as drastic. The ventilation should be activated as soon as possible to control the destratified smoke caused by the activation of the fixed fire suppression system.



Figure 5.4 Photographs of a fire test. (a) Tunnel with smoke stratification at ceiling right before fixed fire suppression system activation. (b) 12 seconds later [full discharge] and beginning of smoke de-stratification. (c) Additional 8 seconds later, showing smoke descending to lower elevations. (d). Additional 8 seconds later, showing smoke at ground level. [50]

Fast, reliable fire detection and prompt activation of the fixed fire suppression and ventilation systems are of vital importance in order to obtain benefits from the combined operation of the FFSS and the longitudinal ventilation system. With the fixed fire suppression system, longitudinal airflow may need to be selected to ensure an appropriate droplet spread and mass flow performance for given water pressures. Otherwise, appropriate fixed fire suppression zones need to be activated depending on the longitudinal airflow.

The ventilation system is also affected by the sprinkler operation. Water curtains create a significant resistance to longitudinal ventilation that is necessary in preventing smoke backlayering. However, the critical velocity requirement may also be reduced due to the reduced fire heat release rate and air temperature. The temperature tenability requirements can be met with less ventilation; however, smoke toxicity and air humidity are a concern. The performance of the tunnel ventilation fans should be evaluated considering lower temperatures, water curtains, and the additional mass of moisture.

With the longitudinal ventilation system, it seems reasonable to activate both systems simultaneously. As a result, the wet fixed fire suppression system will start before the longitudinal ventilation reaches full speed. This allows the sprinkler system to discharge water in a low air velocity environment, thus protecting people and structures by taking control of a fire at an early stage of its growth. Once the ventilation reaches full speed, the sprinkler zones may need to be revisited and either switched or additional activation zones will be required to account for ventilation. The question is: if the sprinkler is activated early enough, can ventilation be reduced or eliminated and what will be the impact on smoke production?

Transverse Ventilation

Transverse ventilation uses both supply and exhaust ducts served by a series of fans usually housed in a ventilation building or structure. Exhaust openings are often located at the ceiling level relying on stratification to extract smoke and hot gases, while stratification could be destroyed by the fixed

firefighting system. However, there are systems with sidewall exhaust air openings which depend less on stratification and more on pressure created by the fans.

Recent scale model testing of an automatic sprinkler system showed that it could be used safely in tunnels with transverse ventilation or where longitudinal ventilation is used at low speeds. Concerns were raised regarding sprinkler system failure as a result of too low water pressure or too high ventilation air velocities.

Longitudinal air velocities for full transverse, semi-transverse exhaust, and single point extraction systems are relatively small and the displacement of water droplets due to ventilation is diminished. However, water droplets will most likely destroy stratification and lower the efficiency of these systems.

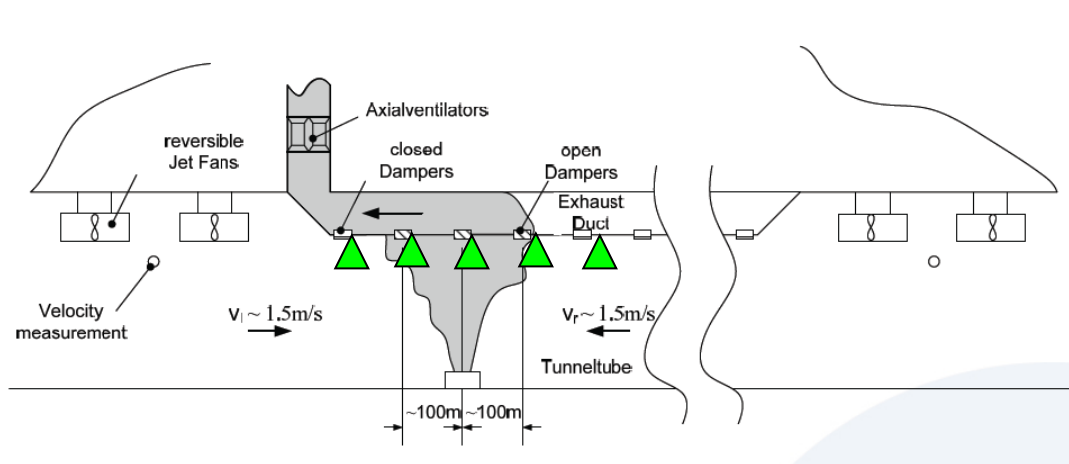


Figure 5.5: Single point extractions with fixed fire suppression system

Since longitudinal air velocities are relatively low with transverse and single point extraction systems, any type of tunnel fixed fire suppression system can be considered. The water mist system may be beneficial since it produces less stratification disturbance, provides a better cooling effect, and is somewhat safer for the mechanical and electrical equipment. However, reduction of visibility in the path of evacuation due to the loss of smoke and hot gas stratification has to be considered. Does the fixed fire suppression system bring additional benefits? Which fire suppression zones should be activated first? Would the delay in sprinkler activation be beneficial? Are there other means of fixed fire protection system activation to mitigate its possible negative impact on ventilation, such as a water shield mitigation system?

Table 5.3: Analysis of fixed fire suppression system impacts on performance of single point extraction ventilation

Activation to support Evacuation (early activation)		Activation to support First Responders (activation after evacuation)		Activation to support Property Protection	
Advantages	Considerations	Advantages	Considerations	Advantages	Considerations
Temperature reduction	Loss of stratification, loss of visibility and toxicity	Temperature reduction	Ventilation mode may need to be changed to longitudinal	Beneficial in early stage	Possible post-cooling spalling needs to be considered
Radiation reduction	Impact on fan design and required airflow rates	Radiation reduction			

Table 5.3 provides a sample analysis of additional benefits and considerations to be addressed when analyzing a fixed fire suppression system in addition to a single point extraction ventilation system. Similar analysis can be provided for other types of ventilation systems. The main benefit of controlling the fire growth and reducing the heat release rate (and thus a reduction in the overall smoke production rate) could be achieved with a reliable and rapidly activated fire suppression system before the fire gets too large.

With a transverse ventilation system using ceiling exhaust, the sequence of activation may differ from a longitudinal ventilation system sequence. Destruction of the smoke layer, worsening of visibility, and potential generation of hot steam must all be considered when developing the system controls. The Japanese approach for the transverse ventilation system allows for a minimum of a 3-minute delay before sprinkler activation so that people can leave the sprinkler zones. However, sprinkler activation delay may be dangerous for the tunnel structure and can lead to fire spread and growth. It may also require a greater water supply, due to a larger fire size at the time of activation. This needs to be evaluated in the design and additional research is required.

The activation time of the FFSS may differ depending on the type of ventilation. There is a need for an integrated approach to all fire life safety system designs to coordinate each element and obtain the desired level of tunnel fire life safety.

5.2 INTERACTION BETWEEN FIREFIGHTING OPERATION AND TUNNEL VENTILATION SYSTEMS

Mechanical ventilation systems are a major factor in ensuring safety, both for tunnel users and emergency response teams. The best chance of successful firefighting is in the initial phase of a fire. It is obvious that FFFS systems are beneficial for emergency and rescue services and could be effective in

protecting the tunnel infrastructure and delivering human safety. See Section 5.1 on interaction between water based fixed fire suppression systems and tunnel ventilation systems.

NFPA 502 [1] states that the “Smoke Control design goal shall be to provide an evacuation path for motorists who are exiting from the tunnels and to facilitate fire-fighting operations”.

As far as fire and rescue services are concerned, the most important measures that can reduce the severity of accidents are:

- short distances to, and simple means of reaching escape routes for those escaping from a fire and rescue work;
- fire fighters can approach the fire as safely as possible and safely escape as needed; and
- fire cannot grow excessively before firefighting work can start.

These various conditions can be achieved in different ways, but there must be an overall safety program that identifies all the parameters involved, ensures that they work together, and creates the best conditions for a high level of safety.

When the evacuation phase is concluded, firefighting must be facilitated by proper smoke management. A basic requirement is to provide maximum opportunity for firefighting access in minimum smoke conditions. During evacuation, the direction of smoke flow must not change. Upon rescue team and fire fighter arrival, it can be decided on-site which mode of ventilation is the most effective for their mission. The ventilation mode should be provided to force heat and smoke or other noxious gases in the direction away from the first responders.

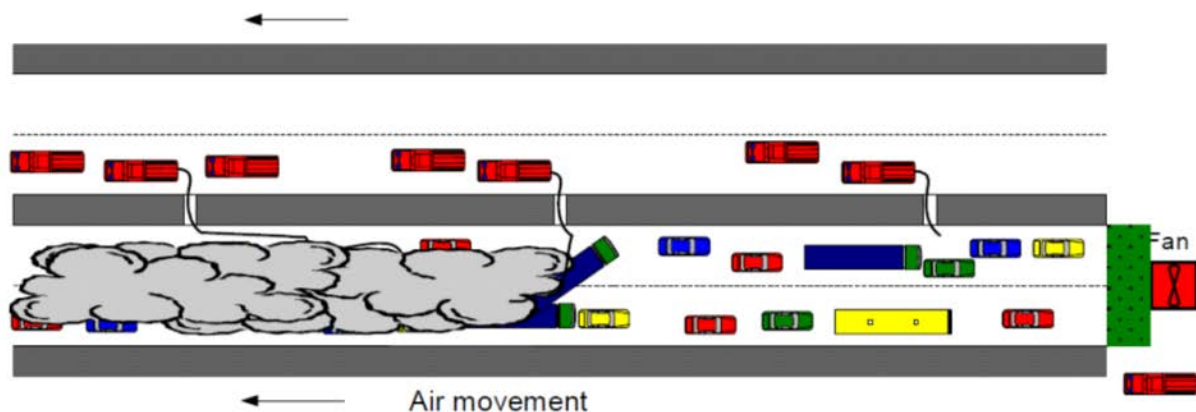


Figure 5.6: Fire and rescue operation dealing with a car fire in a twin-bore tunnel with queuing traffic [18]

The requirements of the emergency services should be taken into account when designing the ventilation system and response procedures for assisted rescue and firefighting phases. Heavy items, such as fans, subject to temperatures of 450 °C (842 °F), are to be designed not to fall during the firefighting phase [43]. In some cases, dedicated firefighting ventilation modes are designed to reverse longitudinal ventilation and to operate at velocities other than ones required for the evacuation phase. Considerations should be given to the time factor for achieving full reverse of smoke management during the fire event and that such operations can take a longer time, depending on the ventilation system, the tunnel geometry, the fans, electrical control system used, and other conditions. Smoke

clearance could also be achieved by the use of portable smoke control equipment deployed by the Fire Services, such as movable ventilation units (MVU).

When the fire department arrives at a fire scene, they may not have the means to reach a fire inside the tunnel because reaching the scene in the conditions of extreme heat and smoke may be beyond the endurance of human beings, even if they have appropriate equipment, such as a long duration breathing apparatuses and firefighting protective clothing.

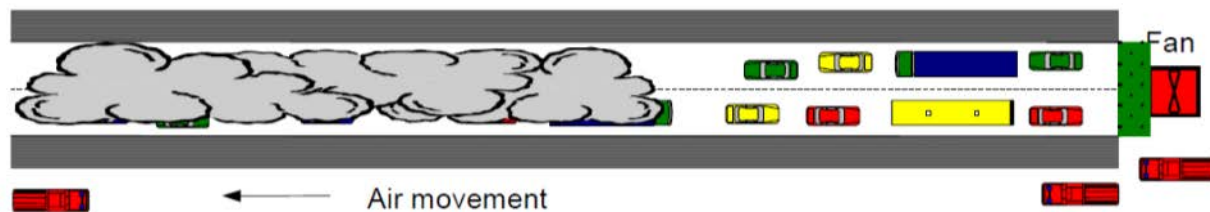


Figure 5.7: Fire and rescue operation dealing with a car fire in a single-bore tunnel [18]

Reversal of jet fans is generally not recommended during the evacuation phase, even if the fire is located near the entrance portal. In the period between the ignition of the fire and the reversal of the jet fans, smoke could have traveled several hundred meters. When the smoke layer flow is reversed, it will spread over the entire cross section during the phases of evacuation. It is important to maintain good visibility conditions. Therefore, only after evacuation is complete can reversal of the air flow direction take place. The Emergency Response time is to be based on NFPA 1710. Figure 5.8 demonstrates a tunnel firefighting timeline. According to NFPA 1710, the fire department's objective is 80 seconds for turnout time for fire response, from 240 to 480 seconds for the arrival of the first engine and from 480 to 610 seconds for the deployment of an initial full alarm assignment. Firefighting time (time of intrusion) will depend on the nature of the incident.

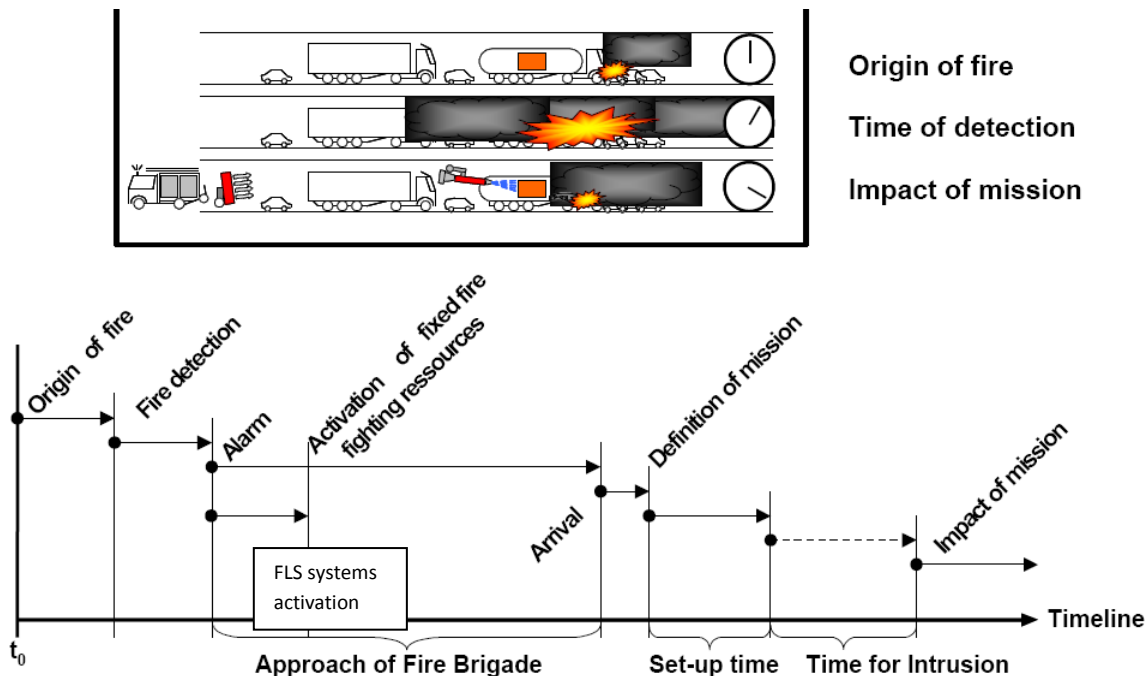


Figure 5.8: Firefighting timeline [51] [52]

Often, the firefighters have to get very close to the fire site in order to fight the fire due to low tunnel ceilings. The water flow rate is sometimes maintained for up to 30 minutes or more in order to extinguish a HGV fire. Ventilation could manage hot gases, but thermal radiation from the fire and from any residual backlayering will be difficult to deal with. Development of some form of protection against thermal radiation such as water mist or a water curtain could assist in tackling fires of this type. Portable radiant barriers and other vehicles already in the tunnel could be used to protect firefighters from thermal radiation.

The design features must be understood by all agencies involved in tunnel safety, the operators, and the various emergency services. If such understanding does not exist, then beneficial, expensive, and complicated design features may not be used in the event of an emergency. An example of this would be the provision of a complex ventilation system for use by the fire department in case of fire. If fire department personnel are unaware of how the system operates, it is unlikely to be used effectively. The tunnel operator must provide expert knowledge and advice on tunnel facilities and the ventilation system to the emergency services incident commander.

An educational plan comprising both education of new employees and repeated education of current employees should be implemented covering all staff dealing with safety, including maintenance contractors. The plan should be a planning and follow-up instrument for individual staff, and acceptable time intervals for different education topics should be incorporated. As part of the education plan, the traffic operators should, on a regular basis, carry out exercises which focus on prevention and handling of incidents/accidents and seldom used procedures.

6 TUNNEL EMERGENCY VENTILATION CONTROLS

Every tunnel project should have a ventilation control philosophy and control design fully developed. The control system should allow for the response of the ventilation system to a reported incident in accordance with the emergency response plan. This response is based on information retrieved from various sources inside and outside the tunnel. The information is analyzed and validated and the ventilation response could be activated automatically, semi-automatically, or manually:

- In automatic control, there is no intervention of the tunnel operator. However, the tunnel operator could intervene in the automatic process. Fully automatic control should be applied for tunnels with no supervision (unmanned tunnels).
- In semi-automatic control, the fire could be automatically detected and the tunnel operator chooses to implement the pre-programmed procedures of the smoke control system. The semi-automatic control system, when started, controls the components of the smoke control system according to a previously programmed procedure associated with the input objectives defined by the tunnel operator.
- In manual control, the operator analyses the available data and activates each component or groups of components of the smoke control system following a procedure that should be pre-defined for the fire event.

Consideration needs to be given to the complexity of the ventilation system and the organization of the operating personnel. For example, for uni-directional tunnels with longitudinal ventilation and managed traffic downstream of the fire, knowledge of which is the incident tube could be sufficient to start the ventilation, while in tunnels equipped with a single point extraction system, information on the exact fire location and air velocities in the vicinity of the fire is crucial. Experience shows that a complex ventilation system is much more efficiently managed by an automatic or semi-automatic system than by an operator performing under high stress conditions. It has become a common practice to develop mode tables according to pre-defined different fire /egress/ventilation scenarios. The mode determines the activation of the ventilation and other fire life safety systems including the FFFS and traffic control, which leads to a single push-button preprogrammed for a specific fire scenario event. The operator should also be able to override the control procedure at any time as he/she may have knowledge of false alarms or an inadequate response procedure.

The ventilation control should ensure adequate response for all conceivable fire scenarios including scenarios where some equipment or sensors fail to respond. All possible fire scenarios should be modeled using CFD or other approved numerical simulation tools at the design stage of the project and the results should be implemented in the mode tables developed for the tunnel. It also requires training of tunnel operators, first responders, and their interactions.

Prior to the activation of the ventilation system, the fire must be “detected”. The tunnel operating procedures may prescribe that the emergency ventilation is activated before full confirmation of a fire as a precautionary measure.

The components of the smoke-control system act on the flow inside the tunnel, changing it in an appropriate way, while changing the measured airflow parameters. Therefore, the control method must take into account that the conditions may change over time. This change could be accounted for in an automatic control system, but would be very demanding in the case of manual control.

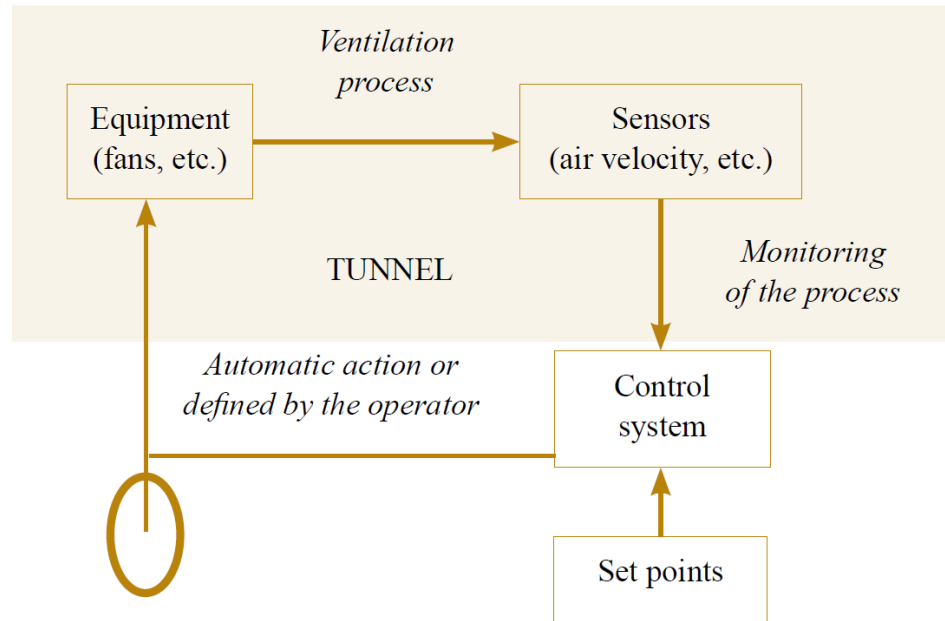


Figure 6.1: Overview of the tunnel ventilation control loop. [15]

Fire emergency situations require rapid response from the tunnel ventilation system. Consequently, the response time for the entire chain of events, i.e. detection, identification, alarm validation, and intervention, must be reduced to establish a tenable environment during the evacuation phase. The best strategy to be adopted depends on the quality and reliability of the available information.

PIARC proposes the following fire detection and validation process flow chart in Figure 6.2 [15]. Once the fire alarm is detected (confirmed as needed only) and the ventilation strategy is defined, the control system must be able to achieve the pre-defined condition (for example, a particular longitudinal velocity). It may be appropriate to place the system in an alert and starting condition even before confirmation of the fire and its location. All steps of the algorithms must be clearly detailed into the specifications.

Variable speed drives with controllers have been recently developed for jet fans, which provide the ability to operate the jet fans at prescribed air velocities as part of the control system. The fan speed can be adjusted based on precise fire detection and adequate airflow measurements in the tunnel. In some control systems, the natural ventilation effects can be calculated in real time to control the ventilation system operation. In the Model-based Predictive Ventilation Control (MPVC), signals from the sensors are passed to the PLC with the MPVC software that chooses the fan settings.

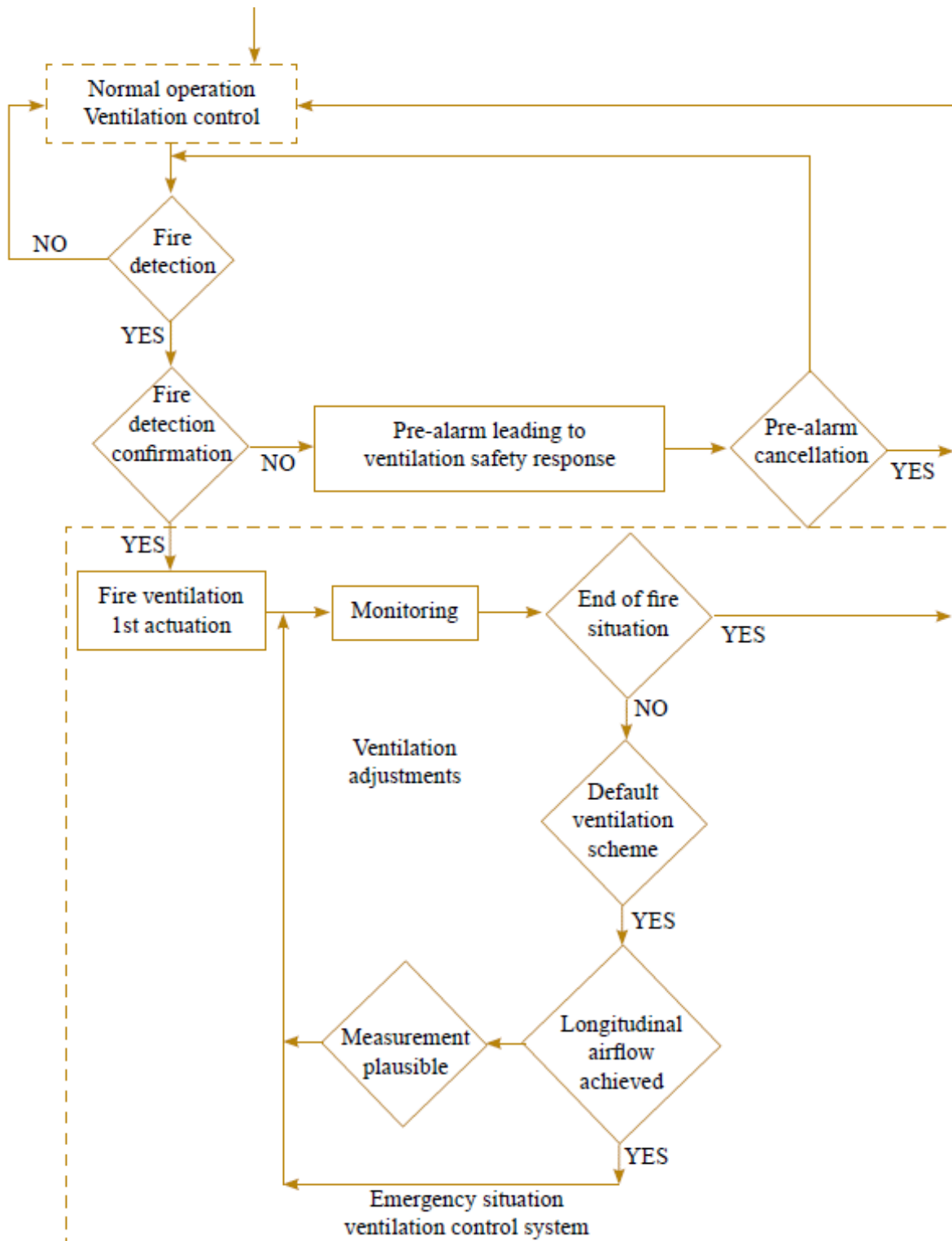


Figure 6.2: Fire detection and validation process flow chart [15]

Ventilation control should be designed along with the control of other systems, such as the fixed firefighting systems (FFFS). There is a variety of controls available to fully integrate the FFFS with the ventilation, operate them separately, fully automate them, automate them with manual override, and

manually operate them with auto override. However, each of these options must be carefully evaluated. Different tunnels may require different approaches. Some approaches may consider automatic activation with or without a time delay and override. Others may consider activation by an operator or by the Fire Department only. The choice of control depends on the objectives of the system. Some tunnels may require a FFSS activation for any tunnel fire event; others may require activation of the FFSS for major fire events only. This is subject to additional research.

Typically, a project establishes a time-of-tenability criterion for fire life safety system design. Figure 6.3 [3] provides an example of such a curve, which shows the fire curve (fire development), self-rescue, and fire life safety (FLS) activation relative to the fire development. This example illustrates that evacuation will start while the fire grows and well before the ventilation mode and FFSS can be fully activated. The only means to get fire growth under control for this example is to activate the FFSS prior to the ventilation system. Ventilation should remove smoke and toxic gases once activated. Considering that the amount of water required for the fire suppression is directly related to the fire size, it becomes critical to activate the deluge FFSS no later than when the design fire heat release rate is achieved on the curve.

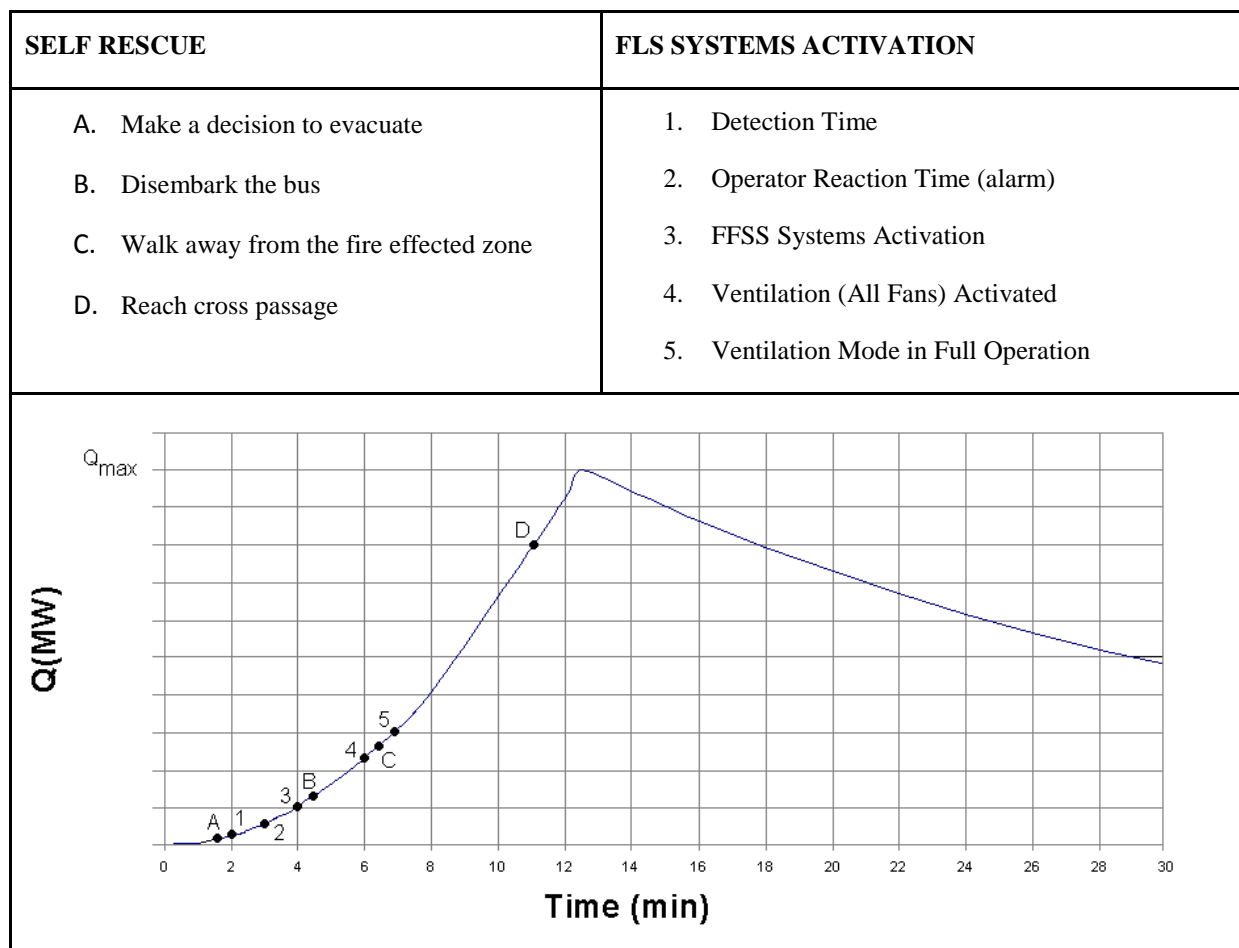


Figure 6.3: Example of project established time-of-tenability curve

Appendix B illustrates the effect of the FFSS suppression on the heat release rate. With timely activation of the suppression system, the heat release rate is reduced. With delayed activation, the fire overwhelms the system and it is not effective.

Some typical problems with ventilation control must be considered:

- Multiple automatic alarms may occur, some of which could be upwind of the fire event far from the incident. This may happen due to the airflow in the tunnel at the time of the incident. Some alarms can be triggered from the gas monitoring systems and a signal to activate normal ventilation can be sent.
- Excessive demand of information from the operator must be avoided and the priority criteria must be established.
- Nuisance alarms
- Lack of operator training for rare fire situations. Training simulators are useful tools for ventilation controls training.

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8 GLOSSARY

AASHTO

American Association of State Highway and Transportation Officials

AFAC

Australasian Fire Authorities Council

AFFF

Aqueous film forming foam

AHJ

Authority Having Jurisdiction

ASHRAE

American Society of Heating, Refrigerating and Air-Conditioning Engineers

Aspect ratio

The proportional relation between the width and height of the cross section of the tunnel which affects the required critical velocity

Backlayering

The reversal of smoke and hot gas movement counter to the direction of the ventilation airflow

BLEVE

Boiling liquid expanding vapor explosion

CCTV

Closed circuit television

CFD

Computational fluid dynamics

Chimney effect

In tunnels that have nonzero grades, particularly those with portals at different elevations, a temperature dependent effect usually referred to as "the chimney effect" is often considered. Air will flow through a chimney (in a direction from the lower portal to the higher portal) because of the difference between the weight of the column of air inside, the chimney (tunnel) and an equivalent column of air outside

Consequence

Outcome of an event in terms of damage to the health of people, to property or environment

Critical velocity

The minimum steady-state velocity of the ventilation airflow moving towards the fire within a tunnel or passageway that is required to prevent backlayering at the fire site

DOT

Department of Transportation

EU

European Union

Event

Occurrence of a particular set of circumstances, which may cause harm

FEDRO / ASTRA

Switzerland's Federal Roads Office

FFFS

Fixed firefighting systems

FFSS

Fixed fire suppression system

FHRR

Fire heat release rates

FHWA

Federal Highway Administration

Fire decay rate

The decrease in the heat release rate of the fire as a function of time

Fire growth rate

The increase in the heat release rate of the fire as a function of time

Fire heat release rate (FHRR)

The rate at which heat energy is generated by the fire typically expressed in megawatts (MW) or MBtu/hr

Fire size

Also equivalent to the maximum heat release rate, the maximum rate at which heat energy is generated by the fire, typically expressed in megawatts (MW) or MBtu/hr

FIT

European Thematic Network Fire in Tunnels

FN curve

Graph with the ordinate representing the cumulative frequency distribution of N or more units of consequence (e.g. fatalities) et abscissa representing the corresponding

consequence. FN curves are used for representing societal risk

Frequency
The number of times a specified event occurs within a specified interval (e.g. accidents per year).

Hazard
Potential source of harm

HRR
Heat release rates

MTFVTP
Memorial Tunnel Fire Ventilation Test Program

NCHRP
National Cooperative Highway Research Program

NFPA
National Fire Protection Association

PIARC
World Road Association

PRV
Pressure reducing valves

Risk
Combination of the probability of occurrence of harm et the severity of the harm [2]

Risk analysis
A detailed examination performed to understand the nature of unwanted, negative consequences to human life, health, property, or the environment

Risk assessment
Overall process comprising a risk analysis et a risk evaluation [2]

Risk evaluation
Procedure based on the risk analysis to determine whether the tolerable risk has been achieved

Smoke stratification
The layering of smoke at the ceiling of the tunnel due to the buoyancy force of the smoke and hot gases leaving a largely smoke free environment below, near the roadway surface

Tenable environment
An environment that supports human life for a specific period of time

TRB
Transportation Research Board

UN
United Nations

APPENDIX A: TUNNEL FIRE DETECTION AND WARNING SYSTEMS

The most common tunnel fire detection principles are based on the parameters determined by the fire and could be applied individually or in combination:

- smoke and gases
- heat
- flames (radiation)

There are a range of methods available to detect fire and smoke within road tunnels including: linear (line-type) heat detection (LHD), CCTV video image smoke detection, flame detection, smoke and heat detectors, spot-type heat detectors, and smoke and gases detection. The selection of the type of fire detection system(s) should be made depending on the fire safety goals/objectives and the overall fire safety strategy, which includes notifying occupants to allow for safe evacuation, modifying tunnel operations, initiating fire life safety systems operations, and notifying emergency responders.

Linear (Line-Type) Heat Detection: There are several types of line-type heat detectors used today. The three main types are: Analog (Integrating) Linear Heat Detectors, Digital Linear Heat Detectors and Fiber Optic Linear Heat Detectors.

- Analog (Integrating Heat Detectors) systems incorporate a multilayer cable. It consists of a core conductor covered by a temperature sensitive semiconductor with an outer conductor. The inner and outer wires are connected to a control panel that monitors the resistance of the semiconductor. A temperature rise in the cable causes a reduction in the conductor's resistance and detection occurs when the monitored resistance reaches a pre-determined setting.
- Digital Linear Heat Detectors consist of two polymer insulated conductors. The insulation melts at a set temperature. Detection in this system occurs when the insulation melts which allows the conductors to make contact with each other. In some systems, the control panel connected to the sensing element is able to determine the distance where the conductors made contact and determine the location of the fire.
- Fiber-Optic Linear Heat Detectors consist of a control panel and quartz optical fibers. The control unit houses a laser that sends a beam through the fiber optic cable. These systems provide detection using the Raman-Effect which senses temperature changes by evaluating the amount of light scattered. The rate of raise of temperature is adjustable and defines sensitivity.

One of the main advantages of this type of detection is that the cable is suitable for harsh environments. In addition, because these products are essentially a two conductor cable, there is flexibility in the installation: patterns can be used to meet spacing requirements and the cable can be routed around obstructions. Many of these products can determine the approximate location of the fire based on either a reduction in the conductor's resistance or light scattered for fiber optic systems. Some manufacturers of these systems also claim a useful system life of about 30 years. Recent tests demonstrated that linear heat detectors can detect shielded and unshielded tunnel fires with desired accuracy within 90 seconds or faster. Their sensitivity can be adjusted for no nuisance alarms and fast detection. Due to such advantages and relative simplicity, they are

currently the most commonly used devices for fire detection in road tunnels. It is important to acknowledge that most of these modern devices have a proven reliable history in road tunnel applications.

There are disadvantages to using linear heat detectors. Their performance can be impacted by tunnel airflow which cools down air temperature, moves heat along the tunnel, and reduces the rate of rise of the air temperature. Some models require replacement of the heat detection cable after a fire event. With tunnels typically being extremely large, long open spaces, providing detection using linear heat detection can require a large amount of cabling. If the objective is to detect a fire from a moving vehicle, such as a tractor-trailer, the design will need to assess whether the cable will be heated sufficiently as the vehicle moves to activate the alarm. It should be noted that some old types of linear heat detection systems failed to detect large size tunnel fires, or detected them too late, or generated numerous nuisance alarms which required their deactivation in the past. There are known past bus tunnel fire events in tunnels furnished with a linear heat detection system which were unable to detect the fire. In addition to airflow, considerations should be given to shielded fires initiated inside or under vehicles or under vehicle's hood, which makes rapid heat detection at the tunnel ceiling level difficult.

Flame Detectors. Flame detectors are fixed devices that are capable of sensing fire by the amount of radiant energy that is emitted. Detectors in this category include UV, IR, combination UVIR, or multiple wavelength IR.

Flame detection systems have a number of advantages. These systems typically work well in and are suited for harsh environments such as those found in tunnels. Some of the more challenging fires in road tunnels involve combustible and flammable liquid. Flame detectors are well suited for detecting these types of fires. These devices are also capable of detecting fire signatures that include a range of varying wavelengths, which provides design flexibility when developing the system.

The latest IR detectors are equipped with a video camera which allows for verification of the fire location. In recent fire tests, the latest IR devices detected road tunnel fires (both shielded and unshielded) within 60 seconds - faster than any other competing devices and with no nuisance alarms over a testing period of a year [49].

Disadvantages for some old systems is that historically, they have been prone to nuisance alarms caused by interference from arc welding, electrical arcs, lightning, metal grinding, artificial lighting and, in some cases, even sunlight. However, some models have a proven successful operation history of over 20 years in Japan where "fire[s] should be detected in 30 seconds or less for a .5 m/sq. gasoline pool fire with wind speeds of 0-12 m/s" [53]. Newer designs account for these interferences. Like many other systems, detection could be delayed when dealing with shielded fires or smoldering fires with invisible flame. They have a long range for fire detection and as a result, several IR cameras installed in a line could detect the same fire, which could cause confusion in identification of the fire zone. The control system should utilize an algorithm which allows for verification and identification of the proper fire zone. Tunnel airflows may also deflect flames which might also impact the accuracy of detecting the correct fire zone.

CCTV Video Image Smoke Detection (VISD) Video detection is a relatively new smoke detection technology that uses real time video images. Through proprietary software, this technology is able to detect fires by analyzing changes such as brightness, contrast, edge content, loss of detail, and motion.

Video smoke and heat detection has a number of advantages. First, the system cameras can be used for other systems such as traffic control monitors, security, as well as smoke and fire detection. Second, detection is based on real-time video images, so each camera can cover a large area. Third, this technology is capable of detecting fires from moving vehicles. Fourth, emergency responders can be provided with real time video information about the fire. The visuals can provide useful information such as fire size, fire source, and the location of the fire, which can help operators and responders efficiently react to the incident.

Interest in the use of the automatic video image detection (VID) system for road tunnel protection has increased because of its quick response to the fire or security incident, real time video images for use in monitoring events, and in guiding evacuation, rescue and firefighting. Many tunnels are already equipped with VID systems for traffic managements and for security protection. Recent studies conducted by the Fire Protection Research Foundation (FPRF) at NFPA also showed that the VID fire detection system was one of the promising detection technologies for use in road tunnel protection.

A new generation of video detection technology is being developed. It includes volume sensors, which look for fire and smoke within the entire observation space of the IP address of the camera. This fundamental advantage results in faster fire and smoke detection and, most importantly, provides a visual picture of the situation to the on-duty operator. Some cameras are both UL Listed and Factory Mutual (FM) approved and have flame and smoke detection devices that are also FM approved. The cameras have passed tunnel tests in Canada, New York and China. Use of camera based detection systems may fulfill multiple purposes if the camera image can be used for security, traffic and/or road conditions.

The main disadvantage of the CCTV Video Image Smoke Detection is the nuisance alarms at the required sensitivity setting for rapid fire detection. To prevent nuisance alarms, multiple detections/confirmations are required before notification or system activation can occur. This also provides redundancy in case one detector fails. When the alarm conditions are met, the event file is created and sent to the remote monitoring station operating the system. The on-duty operator receives the notification of the alarm with live video from the location.

It is recommended to test this system and to review listings and approvals with the authorities to determine the suitability of these devices for specific projects. Because these systems rely on video imaging, some of them may have a difficult time in detecting shielded fires. This is a disadvantage for other systems as well.

Note that the Traffic Surveillance and Control System with pan-tilt-zoom (PTZ) CCTV cameras are often used in tunnels for incident detection. Such systems use image processing algorithms to extract pertinent information from CCTV cameras while providing automatic traffic data collection, travel time, and digital video recording capabilities during an incident, which could be used for fire detection purposes. Tunnel operators could use the video images to verify incident information, and to search and validate the conditions of other tunnel subsystems. Such systems cannot be considered as an automatic fire detection system. However, they could be very effective for verification of fire incidents detected by fire detection devices.

Spot Detection. A number of traditional smoke and heat detection systems were used to detect fires in road tunnels. These systems include the use of projected beam type smoke detectors, duct smoke detectors, and heat detectors.

- Duct Smoke Detectors are provided in the tunnel ventilation ducts. Typically the actual detector is mounted on the outside wall of the duct. The detector is connected to a metallic tube that extends across the duct. The tube has calibrated holes which draw air into the tube that is then directed to the detector.
- There are many different types of Heat Detectors. Typically detection is either by an abnormally high temperature or a pre-determined temperature rise. Some heat detectors are capable of detecting both temperature and rate of temperature rise.

One of the main advantages for these systems is that they are readily available and there is a wide pool of contractors capable of installing these systems, so there is no need to hire a specialized contractor. Compared to the other systems, these systems are relatively inexpensive.

Projected Beam Smoke Detectors typically consist of a detector unit with a receiver. A beam of light is sent from the detector to the reflector and if the beam is obstructed, it will cause an alarm. Disadvantages for projected beam and duct mounted detectors are that they are prone to nuisance alarms from diesel exhaust, which is almost always present in road tunnels. They are also rather slow to detect road tunnel fires when the sensitivity is adjusted to eliminate nuisance alarms.

Application of two different types of fire detection systems in a tunnel significantly enhances the fire detection capabilities and tunnel fire safety. For example, installation of a linear heat detection system along with IR cameras equipped with CCTV ensures that air cooled fires or shielded fires will be detected in a timely manner and easily verified by the operator.

Besides the automatic fire detection systems, fire can also be detected by the tunnel operator using CCTV pan-tilt-zoom cameras installed in tunnels, by tunnel users notifying the operator using manual fire alarm boxes installed at intervals of not more than 90 m (300 ft) and at all cross-passages and other means of egress, or from tunnel users calling 911 and notifying emergency services about the tunnel fire.

Caution is placed when automatic notification is used for the motorists. Tunnel fires may change quickly and can be difficult to predict. Using fire detection systems to decide which direction to exit the motorists and to initiate suppression and ventilation is not foolproof. Directing the escaping motorists in the wrong direction could dramatically increase their risks. However, using automatic detection to close the entrance portal and to warn motorists who are approaching an incident in the tunnel is an accepted practice.

Conversely, using traffic controls to encourage motorists to continue to drive out of the tunnel may be important for tunnels that utilize longitudinal ventilation. In this case, traffic controls downstream of the portal may be essential to clear the tunnel past the incident and to provide room for motorists so that they can drive out to safety before being overwhelmed by smoke and heat that has been pushed along the tunnel by longitudinal ventilation.

These notifications are a key ingredient for the incident command by providing the location, type of incident, conditions and size of the incident. In turn, the motorists can be instructed on what to do while emergency responders are en route and tunnel staff initiates emergency procedures.

Intelligent evacuation notification technologies are now available. They use electroluminescent lighting technology - an uninterrupted illuminated path to the exits with a continuous light source located near the

walkway floor, to be visible in a smoky environment, and a multi directional low level LED guidance system. The advantage of those technologies is that they can be preprogrammed to direct tunnel users in the direction depending on the ventilation system response. This is especially important to eliminate the wrong direction for evacuation when complicated tunnel ventilation schemes are used.

APPENDIX B: TUNNEL FIXED FIREFIGHTING SYSTEMS

Fixed firefighting systems (FFFS) are being installed in many new road tunnels and as retrofits to existing tunnels both within the U.S. and internationally. Today, nearly 200 tunnels around the world are equipped with active fixed water-based firefighting systems. Fixed water-based firefighting systems have been successfully used for more than 50 years in Japan's congested urban road tunnels and, lately, in all of Australia's congested urban tunnels. In the U.S., the system has been first installed in a few tunnels over 40 years ago.

NFPA 502 established the goals of a fixed water-based firefighting system 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 firefighting activities, and/or protect the major structural elements in the tunnel [1]. It should be noted that all water-based firefighting systems are limited in their ability to fight fires inside or underneath vehicles. However, their ability to extinguish small open tunnel fires is recognized. It is to be expected that a fire in obstructed locations will continue to burn after activation of the FFFS. Thus, the main purpose of the FFFS is to mitigate the impact of a fire. Even after activation, tunnel users and emergency personnel should anticipate fire in the tunnel when escaping from or approaching the area of risk.

There are many types of water-based firefighting systems but only a few that are found to be applicable to the tunnel environment. Restrictions, such as open portals, natural ventilation and huge tunnel volumes, prevent the practical application of most suppression systems. The two types of water based fire suppression systems found to present the most benefits in the tunnel environment are deluge sprinklers and intelligent water mist.

- A deluge zone system with open sprinkler heads is the most commonly used system. A deluge water spray system suppresses a fire mainly by fuel surface cooling. This system can be with or without foam additives depending on the type of vehicles allowed in the tunnel and type of tunnel risk level. They are used as fire suppression systems and fire control systems once designed with sufficient water flow for the fire scenario. They can be applied for surface cooling as well.
- A water mist system typically has less water density, higher pressure, and smaller water droplet sizes than the deluge system. A water mist system suppresses a fire mainly by dilution and gas cooling. This system could be very effective as a volume cooling system to cool the tunnel environment using high pressure water mist or as a surface cooling system.
- Other systems such as sprinkler systems with fusible link or high expansion foam systems are less common. Glass bulb type activated fixed water based systems in which sprinklers, spray heads, or other components are activated or controlled individually by thermal elements, such as glass bulbs, are not recommended for road tunnels considering the fire risk present in tunnels and the rapid development of fires and hot smoke. Fire tests have proven that individually activated sprinklers/spray heads do not provide the required level of protection and are very sensitive to the effects of ventilation.

The efficiency of a water based firefighting system is strongly dependent on the size of the fire (or heat generation rate), nozzle type, location, and the water discharge rates.

APPLICABILITY OF TUNNEL FIRE SUPPRESSION SYSTEMS

NFPA 502 does not require mandatory application of a tunnel fire suppression system to all tunnels. The applicability of a tunnel fire suppression system depends on the level of risk the tunnel is exposed to and should be applied to long, high risk tunnels.

Fire suppression systems differ by water density, water pressure, foam additives, and their applicability.

In addition to the objectives discussed in Chapter 5, the applicability of a fixed fire suppression system (FFSS) depends on:

- potential fire risk
- level of protection
- other safety measures in the tunnel
- tunnel geometry
- ventilation/wind conditions during a fire, including interaction with emergency ventilation
- type and performance of the fire detection systems
- activation mode of the suppression system
- any restrictions in positioning and fixing the pipework or nozzles
- distance to emergency exits
- signage and lightning
- thermal conditions in the tunnel and its surrounding
- any specific requirements for the operation of the tunnel

Fire detection and activation of the fire suppression system are essential elements in the design of the fire suppression system and in the ability of the system to meet its objectives, especially for the large fires. For effective deluge operation, activation should be rapid and accurate. If discharged rapidly enough, the fire growth rates will likely be controlled, the risk of rapid fire spread minimized, and toxic gas and smoke generation volumes contained.

If all ignition sources cannot be extinguished and the site is uniformly cooled below a safe temperature, the fire could reignite.

Figure B. schematically shows the effect of a FFSS on HRR [46]. With timely activation of the suppression system, the heat release rate is reduced. With delayed activation of the system, the fire overwhelms the system and it may not be effective.

It is vital to have a clear understanding of the capabilities of the detection system and the lead-in times for activation of the fire life safety systems. If timely detection is not achieved and the fire is not detected until it enters its rapid growth phase, the resultant fire will, in all likelihood, be well beyond the capabilities of a fixed fire suppression system once it is activated [45].

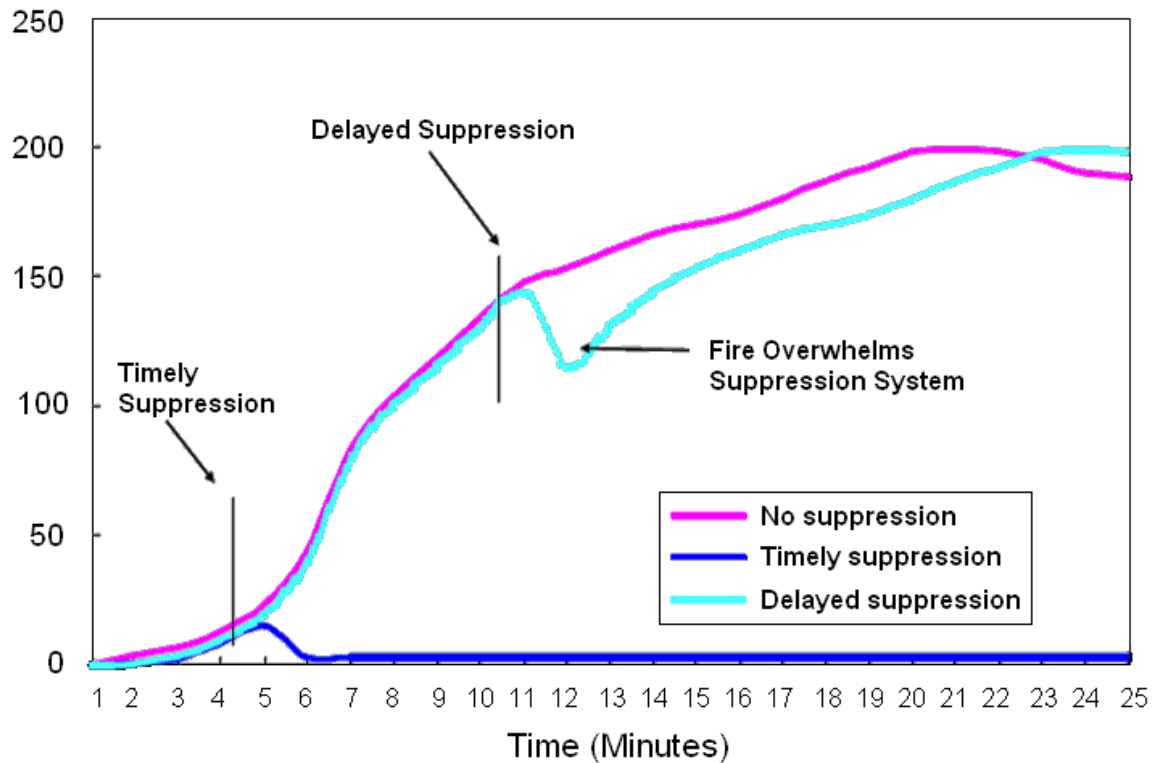


Figure B.1: Schematic effect of suppression on Heat Release Rate. Courtesy of Arnold Dix [46]

While a few automatic sprinkler systems have been installed in tunnels, most systems are deluge systems. The entire protected area is covered with nozzles which are grouped into zones. A deluge system has a network of open nozzles at the roof of the tunnel, divided into zones occupying the entire width of the tunnel. These zones are typically 20 - 35 m (65 - 120 ft) long, a distance which is based off the length of a heavy goods vehicle and the tunnel geometry. When there is a fire, a deluge valve is opened in the zone above the fire and in the zone on either side of it. Water is sprayed from all the nozzles in the activated zones. The sizing of the zone lengths should be based on an analysis taking into account the design fire.

In case of activation of the FFSS (automatically by detection system or manually), at least one deluge valve will be opened accordingly and at least one pump unit will be started. The pump system capacity should be adequate to provide water and, where applicable, additives simultaneously for at least the defined minimum number of zones (normally two or three) at the minimum nozzle pressure at any location in the protected area. Pump system redundancy should be considered. The system should be robust and have a minimum of one redundant pump.

The tunnel fire suppression equipment and piping should be designed based on a hydraulic analysis and should consider a longevity of at least 20 years and operation in a harsh tunnel environment with salted and humid air, vehicle exhaust pollution, particles from brakes, dirt and dust, and should be protected from corrosion. In systems using additives, the temperature of the firefighting agent should be taken into account for the determination of viscosity, depending on the minimum temperature in the tunnel. All materials used should be in accordance with the requirements of the FFSS manufacturer. The FFSS should be protected from damage by vehicles. The FFSS should be designed for operation throughout the range of expected temperatures.

Temperature ratings of all components should be suitable for the operating temperatures during standby and operation. The effects of thermal expansion on pipework which is dry before activation should be calculated by applying an engineering method using a design temperature of at least 250°C (482°F) or at temperatures deemed appropriate.

The impact of water hammer should be taken into account in the design of the FFSS. Water hammer typically occurs in the FFSS when deluge or section valves are closed too fast or empty pipes are filled (system deactivation or changing activated sections). Water hammer creates a pressure surge that can be critical especially for low-pressure systems and their components. Thus, all valves should be designed in such a way that this phenomenon is avoided. Water hammer occurs only if valves are closed faster than the critical valve closing time, which is the time it takes for the pressure wave to travel through the pipework. When defining critical closing time t_c , a safety factor of two should be applied. The calculation for the critical closing time is as follows:

$$t_c = 200\% \frac{2L_{pipe}}{\sqrt{\frac{B_w}{\rho}}} [26]$$

Where

L_{pipe} – pipe length between the pump and the valve

B_w – Bulk modulus of agent (for water at 20 °C: 2.1·10⁹N/m²) [N/m²]

ρ – density (water 20 °C: 998 kg/m³)[kg/m³]

Flushing of the pipework should be planned and carried out according to the manufacturer's requirements. Pipes should be protected with plugs during installation to prevent access of foreign material. Pressure testing should be carried out in accordance with relevant standards at 1.5 times the design pressure and witnessed by the AHJ [26].

Deluge systems have been selected over automatic sprinkler systems for three reasons. First, heat from a fire does not stay over the fire, but travels along the tunnel with airflow. This requires a fire detection and suppression system that can adequately deal with a fire that has heat and smoke dispersed far away from its source. Second, the tunnel fire could rapidly develop a great deal of heat over a large area so that too many sprinklers would open, overwhelming the water supply. Third, automatic sprinklers lack flexibility. By contrast, a deluge system takes a fixed amount of water, and with suitable detection, it is possible to open only the zones above or next to the fire.

Deluge water spray nozzles take water at a typical pressure of 1.5 to 5 bar (21.8 to 72.5 psi) and discharge a pattern of water droplets over the area below. Water spray systems are designed to achieve an even discharge of water over an area, with one specification being the water application density, measured like rainfall in mm/min. Droplets from water spray systems are typically larger than 1mm (0.04 in) in diameter.

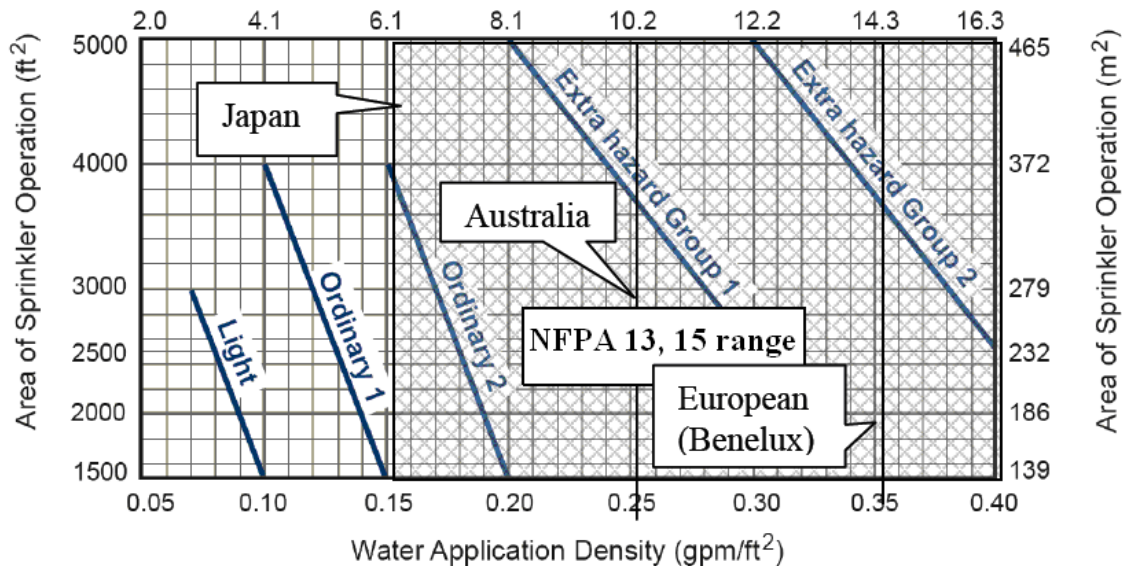


Figure B.2: NFPA 13, NFPA 15, and other International Water Application Rates [47]

Water application rate (water density) should be designed based on the objectives of the system. If the objective is fire suppression, the water density should be evaluated based on the fire HRR at the time the deluge system is fully activated. The deluge systems may require substantial amounts of water, which can have a significant impact on the storage, delivery, and drainage systems. Water mist systems require less water per zone than deluge systems. Japan and Australia each have their own specified water application rates to be used for road tunnel FFFS design, which are 6 mm/min (0.15 gpm/ft²) and 10 mm/min (0.25 gpm/ft²) respectively. In full-scale tunnel sprinkler tests conducted in Europe (2nd Benelux), a water application rate of 14 mm/min (0.35 gpm/ft²) has been tested.

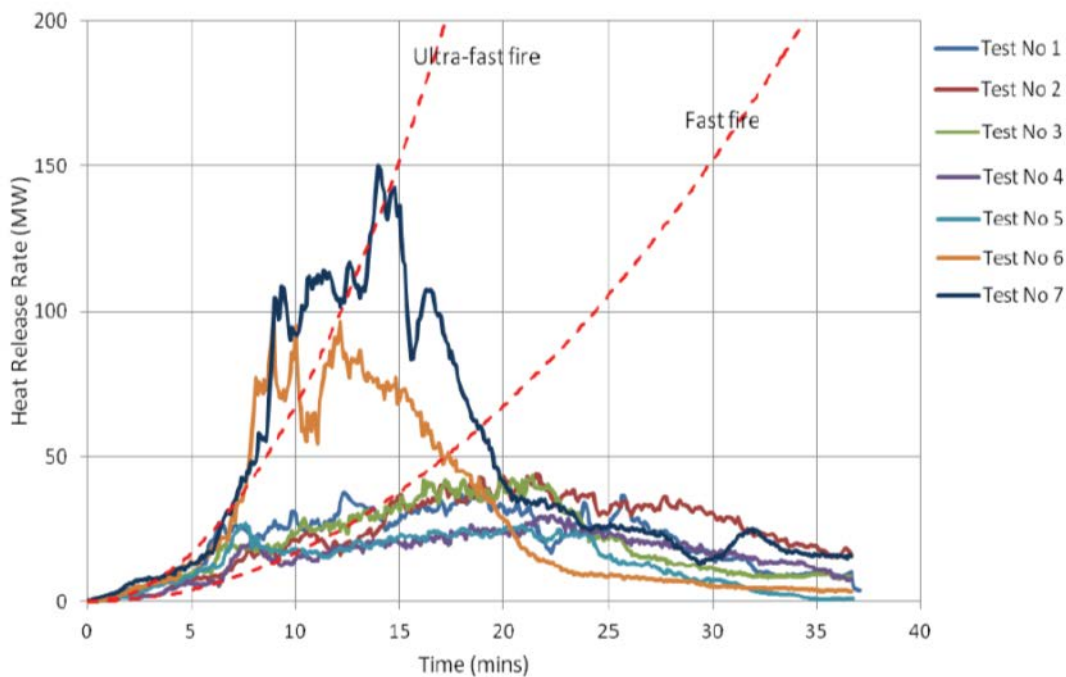
In 2011 – 2012, fire tests were performed at the San Pedro Des Anes test tunnel facility in Spain sponsored by the Land Transport Authority of Singapore. A water flow rate of 8 – 12 mm/min with a nozzle operating pressure of 1 – 2 bar (14.5 – 29 psi) demonstrated the reduction of a fire HRR from 115/150 MW (392/512 MBtu/hr) to less than 40 MW (140 MBtu/hr) when the system was activated at 4 minutes after the fire was detected (see Figure). This corresponded to a 60°C (140°F) gas temperature measurement below the ceiling [48]. The fire test program was carried out for the purpose of investigating the influence of a deluge fixed firefighting system on peak fire heat release rate and to acquire information on the appropriate design parameters (e.g. nozzle type, discharge density, and activation time). The test program included one free burn test and six tests with different deluge system arrangements. All fire tests were carried out with a longitudinal ventilation velocity of approximately 2.8 - 3 m/s (550 – 600 fpm).

Table B.1: Large Scale Fire Tests Schedule [48]

Test	Test description (variation)	Discharge density (mm/min)	Nozzle type	Activation time (min)	Fire in suppression zone
1	Directional nozzle	12	Dir 180°	4	Centre of zone
2	Directional nozzle	8	Dir 180°	4	Centre of zone
3	Standard spray nozzle	12	Standard	4	Centre of zone
4	Standard spray nozzle*	12	Standard	4	Centre of zone
5	Standard spray nozzle	12	Standard	4	End of zone
6	Standard spray nozzle	12	Standard	8	Centre of zone
7	Unsuppressed	n.a.	n.a.	n.a.	Centre of zone

Note: * Test 4 is a repeated test of Test 3

Longitudinal ventilation rate in the tunnel was in the range of 2.8 to 3 m/s



Note: Test 1 to 5 - deluge system operate at 4 minutes (for detail see table 1)

Test 6 - deluge system operate at 8 minutes

Test 7 - free burning

Figure B.3 HRR for HGV Fire with and without fire suppression [48] and with delay 8 min activation of FFSS (test 6).

In U.S. tunnels equipped with a fixed fire suppression system, the water application rate varies from 0.16 to 0.35 gpm/ft² (6.6 to 14 mm/min, see Figure B.) depending on the type of vehicles allowed, the hazards in the tunnel, risk level, and tunnel geometry. Note that 1 kg (2.2 lbs.) of water can absorb about 2.6 MJ (2500 Btu) of heat by evaporation to become water vapor at a temperature of 100°C (212°F). The amount of water required for fire suppression needs to be equal to the heat absorbed by the fuel surface at the time of discharge, rather than the total HRR. Note that to effectively suppress a well-developed fire, the water flow rate needs to be greater to assure that enough water droplets are able to penetrate the fire plume and reach the fuel surface before

evaporation, or that enough water vapor is produced to cool the flame and dilute the combustion mixture. Figure shows the sample curves of fire heat release rates for varying water application rates for unshielded fires. (This example is for illustrative purposes developed only for a specific tunnel geometry and traffic conditions)

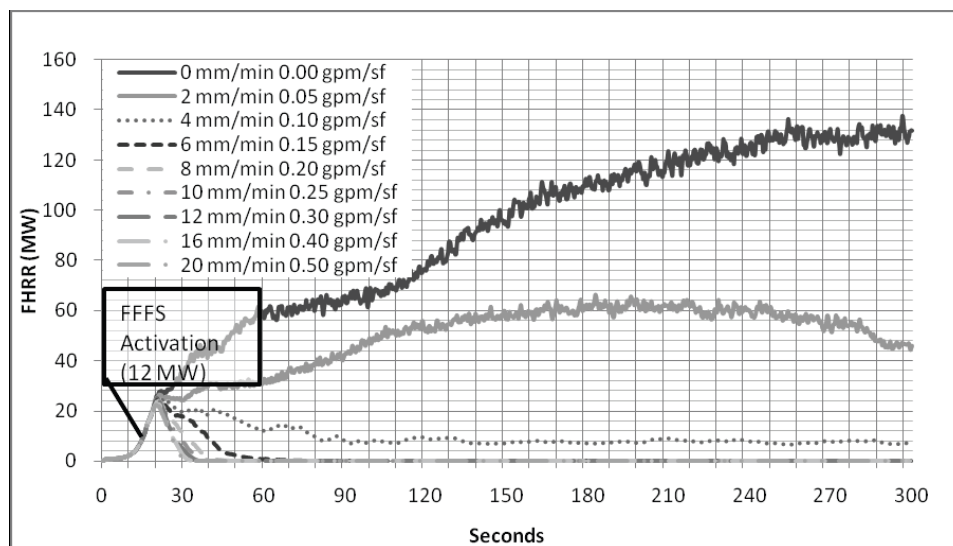


Figure B.4: Fire Heat Release Rate for Varying Water Application Rates-Unshielded Fires [47]

A water based fixed fire suppression system with foam additives such as 3% AFFF (Aqueous Film Foam) should be considered for tunnels that allow flammable and combustible vehicles. This system uses 97% water and only 3% foam which once discharged, creates a thin film of foam on the roadbed surface which isolates light combustible or flammable liquids from oxygen and cools down the fuel pool to suppress the fire. The water density should be calculated the same way as if there is no foam. Tests demonstrated that the system can completely extinguish a small diesel pool fire within 30 seconds after activation and can control a fire if the fuel pool is shielded from direct sprinkler droplets exposure [49]. It was noted that the temperature inside the van was reduced as water droplets were blown into the van through the open windows when the FFSS was active with 3% AFFF additives and a 2 m/s (400 fpm) air velocity was applied to a shielded diesel fire inside the van.

If the objective is volume or surface cooling, the results of the comparative analyses suggest that water application rates as low as 2 mm/min (0.05 gpm/ft²) can offer some benefits by cooling exposed surfaces and assisting in limiting the spread of fire from the initiating point. A water mist system can be effective to achieve the volume or surface cooling objectives.

The water mist system, which gained popularity due to water conservation and saving space within the tunnel, has been installed in several European tunnels and could be effective for volume or surface cooling. A water mist system is similar in zoning and operation to the deluge system with the exception that it utilizes different kinds of water droplets (density, droplet sizes, pressure and so forth). Water mist systems use much lower water density, on the order of 1-4 mm/min (0.024 to 0.098 gpm/ft²). A comparison of a water mist system with a deluge system is shown in Table B.2.

Water mist systems use higher pressures, in some cases over 100 bar (1450.4 psi), and discharge small water droplets, 99% of which have a diameter less than 1mm (0.04 in). Water mist systems can be subdivided into low pressure water mist (about 10 atm [147 psi]) and high pressure water mist systems (in the range of 80 atm [1180 psi]). Nozzles with very small orifices are used to create the mist. The smaller droplets are drawn into the fire and easily evaporate due to the large surface area to volume ratio. The mist systems may require less water per zone. Storage tanks, pumps and pipes can be smaller as well, saving on costs.

To operate effectively, the fixed fire suppression system has to be properly maintained, periodically tested and it must survive the event.

Table B.2: Comparison of water mist and deluge systems components

System	Pumps	Piping	System components	Droplets	Coverage	Advantages	Disadvantages
Water Mist	Yes – high pressure 100 + bar	Stainless steel high pressure tubing	Special nozzles Control panel High pressure valves	Less than 1 mm (0.04 in). Typically 50 (0.002 in) to 300 (0.01 in) microns.	Varies depending on head selection and design fire size	Uses less water Smaller pipe sizes Compact valve box Effective at reducing temperature Components hold up to the harsh tunnel environment	Highly affected by high air velocities High pressure pumps Specialized maintenance
Deluge	As needed	Standard black iron fire pipe minimum	Deluge sprinkler heads UL Listed Deluge valve assembly with butterfly valve, tamper switch and trim (PRV) pressure reducing valves	Over 1 mm (0.04 in)	Varies depending on design fire size	Conventional systems easily maintained Compact valve box design available Well suited to the harsh tunnel environment	Substantial water demand Large distribution pipes PRVs Affected by very high air velocities