NCHRP SYNTHESIS 415

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Design Fires in Road Tunnels

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Design Fires in Road Tunnels

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP SYNTHESIS 415

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The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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Cover figure: Plabutch Tunnel Fire Test
(Graz University of Technology).

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-05, "Synthesis of Information Related to Highways Problem," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measure found to be the most successful in resolving specific problems

PREFACE

By Donna L. Vlasak
Senior Program Officer
Transportation Research Board

This synthesis offers information on the state of the practice of design fires in road tunnels, focusing on tunnel fire dynamics and the means of fire management for design guidance. Information is derived from a literature review and a survey of U.S. and international transportation agencies and tunnel owners and reports on their experience with tunnel fire life safety systems such as ventilation and fire protection and detection. Extensive appendices offer more details about tunnel safety projects, fire tests, and national and international standards requirements, as well as past tunnel fire descriptions.

Basic information is provided for tunnel operators, first responders, and tunnel agencies to better understand their tunnels and train their personnel. It includes statistical data for fire incidents in road tunnels since 1949 through the last decade, as well as statistical data documents for several tunnel fire safety projects that have been established and accomplished in the United States and Europe.

Survey data were also solicited about agencies' experiences regarding problems with systems, gaps in current knowledge, and what improvements agencies would like to see made. Worldwide, a total of 15 agencies reported on their experiences with 319 tunnels yielding a 60% national and 100% international response rate. A majority of the respondents expressed interest in a tunnel fire computer simulator, as only research programs using "Virtual Fires" have been successfully developed and used in Sweden and Austria.

Dr. Igor Y. Maevski, Jacobs Engineering, New York, N.Y., collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

APPENDIXES D–G ARE WEB-ONLY AND CAN BE FOUND AT WWW.TRB.ORG, SEARCH ON “NCHRP SYNTHESIS 415.”

DESIGN FIRES IN ROAD TUNNELS

SUMMARY

There are more than 300 road tunnels in the United States and several thousand more throughout the world. The average age of the U.S. tunnels is more than 40 years. It is often difficult to define whether a structure is a tunnel or a limited-access road under some structure. Tunnels differ by type, length, width, method of construction, and type of traffic. Every tunnel is unique, which makes it difficult to generalize design fires in road tunnels. However, the following general observations can be made based on a literature review and the responses from the transportation agencies to the survey questionnaire for this study.

- By nature, a tunnel is a risky environment. No tunnel is absolutely safe regardless of how it was designed and what types of fire life safety systems were installed. The goal of the tunnel design, operation, and maintenance is to make it as safe as possible based on past experience, on current knowledge, and the development of technical equipment, along with risk and economic issues. The key element is prevention of tunnel fires.
- Most tunnels have fires. On average, based on the survey results conducted for this effort, each U.S. tunnel is likely to experience a fire once or twice a year. However, most of the tunnel events are small and involve cars and vans. The busiest tunnels were found to be more inclined to have fires.
- Major tunnel fires that involve heavy goods vehicles (HGVs) with dangerous cargos and fuel tankers, although rare, can be severe for the tunnel environment. Consequences of tunnel fires can be disastrous for occupants, tunnel structures, and the economy.
- Severe tunnel fires are uncommon and occur less often than fires along open roads. The total number of individuals killed in road tunnels worldwide is fewer than 200, even when including those killed in collisions. Fewer than 20 tunnels worldwide have ever suffered substantial structural damages as the result of a fire emergency.
- Road tunnel fires cannot be completely eliminated until vehicle fires are eliminated.

Analysis of the catastrophic tunnel fire events involving fully loaded HGVs resulted in the following conclusions:

- Tunnel fires develop much more quickly than is expected. Many actual recorded tunnel fires and fire curves show a very fast development during the first 5 to 10 (sometimes 15) min. The gradient of temperature is steep and the emission of heat and smoke is important.
- Fire temperatures in excess of 1000°C (1832°F) can be reached.
- Smoke volumes are higher than expected from an early stage of the fire growth.
- Fire spread between vehicles occurs over a much greater distance than had been previously expected.
- The road tunnel users behaved unexpectedly, such as they:
  - Did not realize the danger to which they were exposed;
  - Failed to use the safety infrastructure provided for self-rescue;
  - Wrongfully believed that they were safer in their cars than if they used the self-rescue safety systems;
  - Chose to stay in their vehicles during the early stages of a fire because they did not want to leave their property behind; and

– Realized too late the danger they had placed themselves in, by which time it was too late to execute self-rescue.

Safety is a result of the integration of infrastructural measures, the operation of the tunnel, and human behavior, as well as preparedness and incident management. The assessment of fire safety in tunnels is a complex issue. It entails broad multi-disciplinary knowledge, the application of different physical models in order to explore the causes and development of fires, and the evaluation of measures to prevent and reduce its consequences.

A design fire is an idealization of a real fire occurrence. A design fire scenario is the interaction of the design fire with its environment, which includes many factors such as the impact of the geometrical features of the tunnel, ventilation, the fixed fire suppression system, other fire safety systems in the tunnel, and the occupants on the scene of the fire.

Given the range of variables and human behavior no one can precisely predict every fire scenario. A design fire scenario represents a particular combination of events associated with factors such as:

- Type, size, and location of ignition source;
- Type of fuel;
- Fuel load density and fuel arrangement;
- Type of fire;
- Fire growth rate;
- A fire's peak heat release rate;
- Tunnel ventilation system;
- External environmental conditions;
- Fire suppression; and
- Human intervention(s).

Therefore, the designer is obligated to make a number of assumptions to ensure that the design will be able to save lives and retain the structural integrity of the tunnel under most of the foreseeable fire scenarios.

A tenable environment is well-defined by NFPA 502 and other standards. To develop a time-of-tenability curve the project must develop:

- A fire heat release curve as a function of time.
- A design evacuation (egress) curve as a function of time.
- A design systems response curve as a function of time.

A tenability map indicates all time steps and resulting impacts on casualties and the tunnel structure. It allows for predicting how long the environment will be tenable in the tunnel and helps to decide what needs to be done to achieve fire life safety goals.

Design fires, which are the basis of the design fire scenario analysis, are described in terms of variables used for quantitative analysis. These variables typically include the heat release rate of the fire, yield of toxic species, and soot as functions of time.

Table 1 summarizes the main design fire variables and provides the range for the variables. It illustrates that time-dependent design fire variables depend on a number of factors to be studied. This table was developed based on the literature review.

The magnitude and development of a tunnel fire depends on:

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

TABLE 1
DESIGN FIRE VARIABLES

Time-Dependent Design Fire Variables	Values Range		Design Fire Variables Are a Function of:
Fire Size—Maximum FHRR	(1.5 MW–300 MW)		Type of vehicle (cars, buses, HGVs, tankers; alternative fuel)
Fire Growth Rate (slow, medium, fast, ultra-fast)	0.002–0.178 kW/s^2 as high as 0.331 kW/s^2 measured at one test		Type of cargo including bulk transport of fuel
Fire Decay Rate	0.042–0.06 (min^{-1})		Fire detection system and delay in activation of FLS systems
Perimeter of Fire	Car—truck perimeter		Ventilation profile
Maximum Gas Temperature at Ceiling	110ºC–1350ºC (212ºF–2462ºF) (higher with new energy carriers)		Fire suppression system
Fire Duration	10 min–2 days		Tunnel geometry
Smoke and Toxic Species Production Rate	20–300 m^3/s		- tunnel width, height, cross section, length
Radiation	From 0.25 to 0.4 of total heat flux up to 5,125 W/m^2 (1,625 Btu/hr/ft^2)		- volume (available oxygen)
Flame Length			- shape of tunnel, grade
			- location of exits
			Tunnel drainage system

FHRR = fire heat release rate; HGVs = heavy goods vehicles; FLS = fire life safety.

- Distribution of fuel load in the vehicle,
- Fire propagation rate, and
- Tunnel and its environment.

Specification of a design fire may include the following phases:

- Incipient phase—characterized by the initiating source, such as a smoldering or flaming fire.
- Growth phase—period of propagation spread, potentially leading to flashover or full fuel involvement.
- Fully developed phase—nominally steady ventilation or fuel-controlled burning.
- Decay phase—period of declining fire severity.
- Extinction phase—point at which no more heat energy is being released.

When there is a fire, carriers of new types of energy can lead to explosions with catastrophic consequences owing to the lack of familiarity with these cargos. The field of new energy carriers is very diverse and constitutes many different fields of research. However, this does not necessarily mean greater risks, but does represent a new situation and implies new risks.

Tunnel ventilation systems are still the main tunnel fire life safety system for controlling smoke and providing a tenable environment for evacuation. However, ventilation may:

- Increase the fire heat release rate and fire growth rate once air velocities are high depending on fire ignition locations.

- Increase the flame length and help the fire to spread farther, assuming the ventilation cooling effect and reduction in radiation at the source are insignificant.
- Affect the performance of a fixed fire suppression system, as well as the ventilation system performance, which is also affected by sprinkler operation.

A fixed fire suppression system can control the fire size, reducing the maximum heat release rate and fire growth rate.

- It is essential that the detection system be capable of detecting a small fire (on the order of 1 to 5 MW). Once a fire is detected early, the fire protection system could take the fire under control and not allow it to grow further, spread to other vehicles, or suppress a small fire. Late fire detection may result in the production of dangerous steam and cause concrete spalling. Sprinklers must not be turned off before the fires are completely extinguished or actively being suppressed by the fire department. Early sprinkler deactivation may lead to explosions and structural collapse.
- Additional considerations are to be given to the impact of fixed fire suppression systems on smoke stratification, visibility, and steam generation during the evacuation phase.
- Major progress has recently been made in fire-detection technology, which helps the ongoing development of fixed fire suppression applications for road tunnels.

A questionnaire response rate of 60% was received from U.S. participating agencies, with additional responses from 100% of the international participating agencies. A total of 15 agencies reported on 319 tunnels worldwide. Participation of national agencies was based on the number of long tunnels in the area. International agencies responded to the same questions to obtain the best international practice. The active international participation was the result of the support and efforts of the Ministère des transport du Québec. U.S. responses were obtained from the following states: Colorado, Virginia, New York, New Jersey, Maryland, Pennsylvania, California, Washington, and Oregon.

The international agencies that responded were from the following countries: Sweden, Hungary, South Korea, Canada, and Australia.

Nine U.S. agencies reported on a total of 32 tunnels ranging in length from 1000 m to 2600 m (3,000 ft to 8,500 ft). Six international agencies reported on a total of 287 tunnels of varying lengths.

The following are some of the findings and lessons learned from the survey:

- Many agencies would consider protecting tunnels with a fixed fire suppression system if proven effective. Future studies are needed to address this area of technology for tunnels.
- Most agencies rely on closed-circuit television for fire and incident detection. Technology needs to be further developed for heat and smoke detection, as well as be tested and listed for fire-detection applications in a tunnel.
- It is important to continue the development of tunnel ventilation systems and ventilation response in conjunction with other systems such as fixed fire suppression systems.
- Specifications for the fire life safety tunnel devices need to be further developed. Reliable and maintainable devices that are designed for the tunnel environment, considering the typical tunnel cleaning and washing operations, chemicals and pollutants present, and dirt and debris build up could become commercially available. One example is locating a commercially available pull station system (a wall-mounted initiating device that is used in a fire alarm system, and located near emergency exits) for a roadway tunnel that is reliable for a long time.
- There is a need for learning the best practice of operating tunnels open to fuel tankers. Such experience exists and best practice can be studied for both design and operation. Banning dangerous goods from tunnels could unnecessarily create adverse economic impact.

Most U.S. tunnel agencies and almost half of the responding international agencies expressed interest in additional training tools for operators who manage fires using a tunnel fire systems simulator. Research programs, using "Virtual Fires," have been successfully developed and used in Sweden and Austria. Using such experience can help tunnel operators, first responders, and tunnel agencies better understand their tunnels and train their personal accordingly.

This synthesis is a report on the state of knowledge and practice for design fires in road tunnels and includes discussions over 13 chapters on the following topics:

- Several tunnel fire safety projects have been established in the United States and in Europe. This report analyzes and provides the major conclusions derived from those research projects and their impacts on the design for tunnel fires.
- This report explains the tenable environmental requirements as defined in NFPA 502 and clarifies some of those requirements.
- A detailed collection of the latest major tunnel fire incidents is presented in this report, followed by analysis of their cause, frequencies, and consequences.
- Combined use tunnels are classified with examples; however, no information on fire incidents in those tunnels was collected.
- This report provides a detailed discussion on the full-scale fire tests performed worldwide. Full-scale fire tests provide most of the input for tunnel fire safety design. Lessons learned and conclusions from those tests are essential for the evaluation of old and new systems and technology. Special attention is given in this report on fire tests with the fixed fire suppression systems and the lessons learned from them.
  - Although full-scale tests are important, they are affected by outside conditions and always limited owing to a limit on available funds. That is a reason why small- and large-scale experiments bring additional value for research and validation of computer models results.
  - Numerical modeling is discussed, including capabilities, limitations, warnings, and research benefits.
- Special attention is given to the design for tunnel fires, including the design fire heat release rate, temperature development, fire gases, smoke and soot generation, and the means of modeling and calculations.
- A comparison analysis is given on standards and guidelines used worldwide. This helps for the further development of national standards and recommendations on the design for tunnel fires. The comparison analysis was made on tunnel ventilation, fire protection, fire detection, and tunnel egress and ingress.
- Design fire scenarios for numerical modeling discuss time-of-tenability and time–temperature curves. They call for an integrated approach toward the fire life safety systems design.
- Studies were made on the effects of various ventilation conditions, tunnel geometry, and structural and nonstructural components of a tunnel on the design fire characteristics. This allows for the interpretation of the results of the Runehamar Tunnel tests and information provided in the standards.

CHAPTER ONE

INTRODUCTION

BACKGROUND

This synthesis reports on the state of knowledge and practice for design fires in road tunnels. It includes a review of the literature and research on current practices. A survey of transportation agencies and tunnel owners to obtain their experiences and practices with tunnel fire life safety systems such as ventilation, fire protection, and detection is included. The survey solicited transportation agency opinions regarding problems with these systems, gaps in the current knowledge, and what improvements they would like to see made.

There has been considerable growth in tunnel construction in the United States and worldwide, as well as an increase in road traffic. This has resulted in a societal concern with tunnel safety. Over the past several years, fires in road tunnels from large vehicles have shown the risks and consequences of inadequate prevention. More than 50 individuals have died in road tunnel fires in Europe over the last 10 years. The national fire analysis and research that was done in 2008 concluded that a fire occurs in a structure once every 61 s. Fires occur in vehicles once every 134 s, and there were 236,000 vehicle fires in the United States in 2008. In 2008, 350 individuals died in highway vehicle fires in the United States. Recent catastrophic tunnel fires have not only resulted in loss of life and severe property damage, but also left the public with a decrease in confidence in the building and operation of new and existing tunnels. Although over the years much research has been carried out on tunnel safety, there are still many gaps in tunnel fire information that can cause difficulties for tunnel designers.

Several NCHRP research studies, work by the TRB Access Management Committee, and publications by TRB, AASHTO, ITE, FHWA, NTSB and others have provided information and materials to state and local agencies on tunnel safety. *NCHRP Report 525: Volume 12, Making Transportation Tunnels Safe and Secure* (*TCRP Report 86*) addresses tunnel safety and security issues (*1*). The International Technology Scanning Program, sponsored by AASHTO and FHWA, issued a report in 2006, *Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response,* with the objective of discovering what is being done internationally for underground transportation systems with regard to safety, operations, and emergency response (*2*). A number of recommendations and design manuals have been issued by the FHWA, including *Road Tunnel Design and Construction Manual* 2010 (*3*) and *Recommendations for Bridge and Tunnel Security* (*4*). A Domestic Tunnel Scan conducted in August and September 2009, lead to the report, *Best Practices for Roadway Tunnel, Design, Construction, Maintenance, and Operation* (*5*).

This synthesis report provides a literature review and synthesis analysis of the latest available information, current practice, knowledge, and relevant research information related to design fires in road tunnels. It includes a collection and documentation of statistical data of fire incidents in road tunnels since 1949 through the last decade; collection and documentation of existing data from fire tests in road tunnels; and identification of the gaps in this information. This information was organized into a concise document that describes current knowledge and practice. The final report provides practical solutions for fire life safety problems.

The report includes:

- Different design standards, guidelines, documents, and codes used worldwide.
- A synthesis of the results of different international projects and their recommendations.
- Tunnel fire events worldwide and their consequences.
- Tunnel fire tests results, including full- and small-scale experiments and gaps in those tests.
- The latest developments, lessons learned, and identification of gaps in available information to provide a foundation for design guidance.

This synthesis report is focused on tunnel fire dynamics and means of fire management for design guidance. The objective of the study was to synthesize the available information related to design fires in roadway tunnels, identify gaps in that information, and provide a framework for design guidance. The information obtained for this project can help state departments of transportation (DOTs), industry, and other stakeholders as a basis for design guidance in making tunnels safer.

PROJECT OVERVIEW

Every tunnel is unique, which makes it difficult to generalize design, and fire safety needs to be reviewed in an integral fashion. This comprises all aspects of fire safety, including the severity of incidents, consequences of fires, human response, structural response, systems response, emergency response teams, and tunnel operators.

The design fire parameters used for the design of tunnel emergency ventilation and fire life safety systems have a significant impact on the tunnel design and users' safety. The key criteria are the fire size and heat release rate (HRR), fire growth and decay rate, smoke production, resultant temperatures, and fire duration. If both the growth rate and the peak fire size are assumed to be too slow in the early design stage, the design changes may result in additional surface penetrations, larger fan plants, and additional spaces and evacuation routes.

More than 30 years ago minimum attention was paid to fires in tunnel design. Tunnel ventilation system design was driven by carbon monoxide (CO) dilution requirements for normal operation and the American Society for Heating, Refrigeration, and Air Conditioning (ASHRAE) recommendations of 100 cfm/lane/ft (0.155 m^3/s/lane/m) of supply and exhaust airflow. However, tunnel accidents in recent years have drawn widespread attention to the risks of fires in tunnels with two distinct consequences. First, the fires themselves have resulted in fatalities, injuries, and structural damages, as well as lengthy tunnel shutdowns resulting in adverse economic impacts. Second, the perceived risk of fire is also likely to have discouraged tunnel use and, in some cases, the actual construction of tunnels.

NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways, updated in 2011, is the primary national document that provides guidelines for fire and life safety requirements for U.S. road tunnels. This standard is generally updated every 3 years based on the latest information on tunnel fires, development of technology, and the experiences of tunnel owners, agencies, first responders, designers, and vendors. The latest Standard includes 13 chapters and an annex of explanatory material that covers limited access highways, bridges, road tunnels, and roadways beneath air-right structures and sets design requirements for fire life safety systems, structures, and emergency response procedures.

ASHRAE established Technical Committee TC 5.9 on Enclosed Vehicular Facilities to address tunnel safety issues during bi-annual ASHRAE meetings through conferences, transactions, forums, and seminars.

Since 1999, a number of major tunnel fire incidents have occurred in Europe. As a result, several international and European research projects have been focused on the design for controlling fires. Ample experience comes from Australia and Japan, who have also had major tunnel fires. Every year there are a number of international conferences, symposiums, forums, and seminars on tunnel safety and the ventilation of vehicular tunnels. This synthesis project focuses on the latest international experience and knowledge in the design of controlling tunnel fires, as well as the survey results from questionnaires completed by tunnel owners and agencies regarding best practice in tunnel safety.

This study synthesizes the available information, practice, and knowledge related to design fires in road tunnels and identifies gaps in that information to provide a foundation for design guidance. A design fire is characterized by a number of parameters including the temperature, fire heat release rate (FHRR), fire growth rate, fuel load, and products of combustion.

The sources of information used for developing this synthesis included the literature search, a survey, and interviews with the following stakeholders: owners, operators, designers, emergency responders, government agencies, relevant professional associations, and so forth. The literature search included national and international standards and guidelines on road tunnel safety; publications of international organizations such as the World Road Association (Association mondiale de la route; PIARC), United Nations, and European Union; reports on major international studies; papers presented at national and international symposiums; and books, magazines, and other publications.

The objectives of this study were to:

- Document significant fire incidents, domestic and international, in road tunnels.
- Review existing data from fire tests in road tunnels and identify gaps in testing.
- Collect data on the application and effectiveness of fixed fire suppression systems and how these might modify the design fire size.
- Document the effects of various ventilation conditions, tunnel geometry, and structural and nonstructural components of a tunnel on design fire characteristics.
- Document the impact of alternate fuel vehicles on design fires.
- Present design fire issues relevant to fire suppression system designs and gaps in available information.
- Establish the state of practice in computer and scale-modeling efforts.
- Provide exit strategies and motorist notification systems.
- Review design guidance information on the issues that need to be considered in setting design fire sizes and establishing next steps.
- Seek out information on combined use tunnels.

DESCRIPTION OF THE SURVEY PROCESS

The survey process involved the development and distribution of an on-line questionnaire that focused on identifying the range of current practices in design and procedures that deal with fires in road tunnels. The primary candidates for completing the questionnaire were transportation agency staff, primarily at the state DOT level, to obtain as broad a representation of current tunnel fire management practices as possible. Input was solicited from the national tunnel agencies and operating authorities. The same questionnaire was sent to international agencies in Canada, Australia, Hungary, Korea and Sweden. The questionnaire responses were a vital source of information for this study.

The questionnaire information was also distributed at the winter 2010 ASHRAE Meeting of the Technical Committee 5.9 on Enclosed Vehicular Facilities to solicit voluntary participation.

The questionnaire was administered in the following manner:

- A targeted list of key individuals at state DOTs was developed. Topic Panel members reviewed the survey distribution list and made changes where necessary and added contact information for any suggested agencies to include in the survey.
- Electronic copies of the questionnaire were distributed to any willing participants.
- Nonrespondents at state DOTs were contacted with follow-up reminders to encourage responses.

Questionnaire recipients were asked to either complete the questionnaire themselves or forward the questionnaire to another, more appropriate individual within their agency. In addition, a recipient could choose to forward the questionnaire hyperlink to individuals in multiple divisions within the agency.

Chapters two through seven, nine, and thirteen document the literature review; results of the survey are summarized in chapter eight; chapter ten compiles design guidance, standards, and regulation; chapter eleven reviews design fire scenarios for fire modeling; chapter twelve discusses fixed fire suppression; and chapter fourteen presents the conclusions and areas for further study.

Appendix A includes the survey questionnaire, Appendix B is a list of the responding agencies, and Appendix C is the Summary of the Survey Questionnaire Responses. Appendixes D through G present web-only information on tunnel safety projects, fire tests, national and international standards requirements, and past tunnel fires.

CHAPTER TWO

TUNNEL SAFETY PROJECTS—LITERATURE REVIEW

OVERVIEW OF RECENTLY COMPLETED AND ON-GOING TUNNEL SAFETY PROJECTS

There are a number of recently completed and on-going projects on tunnel safety and design for tunnel fires in the United States and Europe (see Figure 1). Each project addresses different components of design practice for tunnel fires. Results of these projects findings are documented in this chapter.

PREVENTION OF TUNNEL HIGHWAY FIRES

Prevention and Control of Highway Tunnel Fires (FHWA-RD-83-032): The principal investigator interviewed 18 U.S. agencies operating 35 vehicular tunnels for this study. Responses from single agencies operating more than one tunnel (such as the Pennsylvania Turnpike Commission) carry more numerical weight than others that operate one. The numbers illustrate the range of opinions, practices, and systems encountered. This FHWA publication (*7*) states that:

1. Trucks, in general, have an accident frequency that ranged from 6.89 to 7.50 accidents per million miles (4.28 to 4.66 per million kilometers) from 1976 through 1981. In comparison, tank trucks had an accident frequency that ranged from 3.97 to 5.98 accidents per million miles (2.47 to 3.72 per million kilometers) for those same years. It was noted that tank truck operators may have a more favorable accident history than general truck operators.
2. Few truck accidents resulted in fires (1.7% of all truck accidents). Hazardous material tank trucks had a 70% higher fire-to-accident ratio than the general trucking industry, with 2.9% of all accidents resulting in fire during the period from July 1966 through December 1968.
3. Approximately 50% of the reported fires were caused by collisions. The remaining 50% were caused by non-collision type accidents, such as overheated brakes or tires, defective exhaust systems, and defective electrical systems. Control of hazardous material tank truck tunnel crossings may reduce the probability of collision accidents and subsequent fires. However, inspection of hazardous material tank trucks before tunnel crossings also appears to be needed if the anticipated fire frequency is to be reduced appreciably.
4. Hazardous material tank truck accidents resulted in cargo being spilled in 8.5% of the accidents.
5. The cargo was involved in 87% of the fires involving hazardous material tank trucks.

This information was used to calculate a hazardous material tank truck fire frequency for highway tunnels. The FHWA report states that:

- The average tanker truck accident frequency was 4.91 accidents per million miles (3.05 accidents per million kilometers).
- Assuming that 8.5% of the accidents resulted in spilled cargo, the number of cargo spills per million miles was estimated at 0.418 (4.91 accidents per million miles times 0.085 cargo spills per accident equals 0.418 cargo spills per million miles or 3.05 accidents per million kilometers equals 0.259 cargo spills per million kilometers).
- Assuming that 2.9% of the accidents involving tank trucks result in fires, the number of fires per million miles of tank truck travel are estimated at 0.142 fires per million miles (4.91 accidents per million miles times 0.029 fires per accident equals 0.142 fires per million miles) or 0.088 fires per million kilometers.
- Assuming that 87% of the tank truck fires involve the cargo, the cargo fire frequency is estimated at 0.124 cargo fires per million miles (0.142 fires per million miles times 0.87 cargo fires per fire equals 0.124 cargo fires per million miles) or 0.077 cargo fires per million kilometers.

The fire and hazardous cargo spill frequency for the Reference Tunnel are predicted by using these frequencies (*7*):

1. One cargo spill per 2,390,000 tunnel crossings.
2. One cargo fire per 8,064,000 tunnel crossings.

Assuming that hazardous material tank truck crossings occur at the rate of 100 crossings per day (36,500 crossings per year), the hazardous material fire and spill frequencies are predicted as (*7*):

1. One cargo spill occurring every 65 years.
2. One cargo fire occurring every 221 years.

The incident frequencies for other tunnel lengths or for a different number of hazardous material tank truck crossings may be calculated in a similar manner.

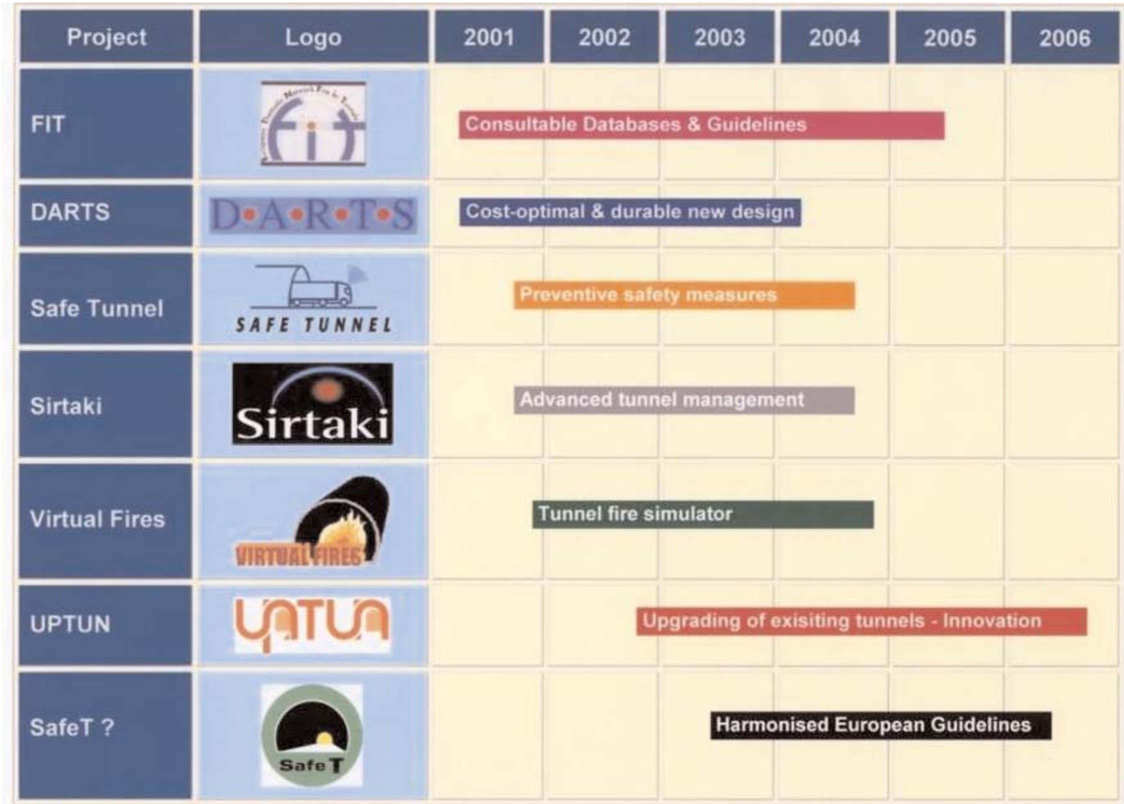

FIGURE 1 Seven recently accomplished European projects on tunnel safety (*6*).

This study demonstrates the risk of tanker truck and heavy goods vehicle (HGV) accidents in road tunnels. Those vehicles provide the most dangerous, largest, and most rapidly growing category of fires.

MAKING TRANSPORTATION TUNNELS SAFE AND SECURE

NCHRP Report 525: Surface Transportation Security and *TCRP Report 86: Public Transportation Security* series publications have jointly published *Making Transportation in Tunnels Safe and Secure* (*1*). The report is Volume 12 in each series.

This research project was developed to provide safety and security guidelines for transportation tunnel owners and operators (*1*). 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 international 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 such that, if damaged, they may be returned to full functionality in a relatively short period of time. It 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 covers the following topics:

- 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.

This report also focused on tunnel structural and vulnerability analysis.

INTERNATIONAL TECHNOLOGY SCANNING PROGRAM—SUMMARY

An 11-member team was formed to study European practices on the aforementioned topics. The team consisted of representatives from FHWA; state DOTs; Bay Area Rapid Transit District (BART); Massachusetts Turnpike Authority, who also represented the International Bridge, Tunnel, and Turnpike Association; plus a design consultant and the report facilitator. The scan was sponsored by FHWA, AASHTO, and NCHRP. During late September and early October 2005, the team visited Denmark, France, Norway, Sweden, and Switzerland. In addition, the team had meetings with representatives from Austria, Germany, Italy, and the Netherlands. These countries were selected on the basis of desk scan findings that showed that they are innovators of underground transportation systems.

The objectives of the scan were to learn what is being done internationally for underground transportation systems in the areas of safety, operations, and emergency response. The focus of the scan was on equipment, systems, and procedures incorporated into modern underground and underwater tunnels by leading international engineers and designers. The study considered the following:

- Tunnel systems and designs that provide fire protection, blast protection, and areas of refuge or evacuation passages for users.
- Arrangements of the various components to maximize their effectiveness, assure that it can be inspected and maintained, and promote cost savings.
- Tunnel operations, including incident detection and deterrent technology, and incident response and recovery planning.
- Specialized technologies and standards used in monitoring or inspecting structural elements and operating equipment to ensure optimal performance and minimize downtime during maintenance or rehabilitation.

Regarding the safety and security aspects, the team was interested in learning about planning approaches, standards, manpower roles and responsibilities, communication techniques, and state of the art products and equipment used to deter, detect, deny, defend, respond to, and recover from both natural and manmade disasters and other incidents.

Team members were interested in not only tunnel practices and innovations for highways, but also for passenger and freight rail. The results of this project were published as *Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response* (2).

The scan team learned that the Europeans consider response and safety measures already in place for crashes and other incidents to also be applicable for many terrorist actions.

Europeans are providing extensive research, resulting in innovative design and emergency management plans that consider how people react in tunnel emergencies. Because motorist behavior is unpredictable in tunnel incidents, Europeans provide instructions for drivers, passengers, and tunnel operators as straightforward as possible to reduce required decision making during an incident, such as a tunnel fire. Appendix D (web-only) provides additional information on nine initiatives and practices related to human factors, planning, design, and incident and asset management that came from the International Technology Scanning Program.

UPTUN—SUMMARY

The UPTUN project was carried out within the fifth framework program of the European Union by a consortium in which 41 partners from 19 European countries worked together from 2002 to 2006 (*8*). The primary objectives of the UPTUN project were:

- Development of innovative technologies. The focus was on technologies in the areas of detection and monitoring, mitigating measures, influencing human response, and protection against structural damage. The main output is a set of innovative cost-effective technologies.
- Development, demonstration, and promotion of procedures for safety-level evaluation, including decision support models, as well as knowledge transfer. The main output was a risk-based evaluating and upgrading of models.

The desired spin-off of the UPTUN project was:

- The restoration of confidence in tunnels as safe modes of transportation systems.
- Reducing trade barriers caused by evidently unsafe tunnels.
- An increase in the awareness of stakeholders for the necessity to develop initiatives to link all relevant research.

The project was specifically targeted at ensuring a pan-European approach toward the improvement of fire safety in European tunnels.

The work was divided into seven technical work packages:

- WP 1: Prevention, detection, and monitoring.
- WP 2: Fire development and mitigation measures.
- WP 3: Human response.
- WP 4: Fire effect and tunnel performance; system structural response.
- WP 5: Evaluation of safety levels and upgrading of existing tunnels.

- WP 6: Fire effects and tunnel performance; system response.
- WP 7: Promotion, dissemination, education and training, and socioeconomic impact.

The first four work packages were designed to increase insight and develop new measures to reduce probabilities and mitigate consequences of fires in tunnels. The fifth and sixth work packages were primarily focused on the development of the innovative integral upgrading approach. The final work package (WP 7) promoted and disseminated the results. The work packages tasks and objectives are discussed in Appendix D (web-only).

FIT

FIT is the European Thematic Network on Fire in Tunnels. FIT provides a European platform for dissemination and information of up-to-date knowledge and research on fires and tunnels. FIT represents 12 European countries with 33 members (*9*).

The following main objectives have been identified for the FIT Thematic Network:

1. The network had as its main objective the dissemination of road tunnel design results obtained from European and national projects. The aim was to optimize research efforts, reach critical mass, and enhance its impact at the European level by combining the results of the different projects.
2. FIT established a set of consultable databases containing essential knowledge on fire in tunnels.
3. A third common objective of the network members was to disseminate recommendations on design fires for tunnels.
4. Consequently, FIT also had as an objective developing a European consensus for fire safe design on the basis of existing national regulations, guidelines, code of practices, and safety requirements.
5. The final objective was the definition of best practices for tunnel authorities and fire emergency services on prevention and training, accident management, and fire emergency operations.

The FIT work plan defines six work packages with corresponding deliverables and milestones that are further summarized in Appendix D (web-only):

1. Consultable databases on fire and tunnel topics [road tunnel design projects, test-sites, computational fluid dynamics (CFD), equipment, fire accidents, and upgrading of tunnels].
2. Recommendations on the design fire scenarios (report).
3. Compilation of guidelines for fire safe design (report).
4. Best practice for fire response management (report).
5. Information and communication (website, newsletter, and workshop).
6. Management.

DARTS

DARTSs stands for Durable and Reliable Tunnel Structures (*10*). The objective of DARTS was to develop operational methods and supporting practical tools for the best proactive decision-making process. Its focus was to compile the optimal tunnel design and construction procedures regarding environmental conditions, technical qualities, safety precautions, and long service life. The approach is based on a minimum total life-cycle cost, including operation and maintenance, and aims to optimize safety and reliability, create the best environment and safety for users and establish the best benefit for society and the owner.

DARTS was developed for the most common current types of tunnels: rock tunnels, bored tunnels, New Austrian Tunneling Method tunnels, immersed tunnels, and cut and cover tunnels.

The project, a partnership of eight European companies, was undertaken from 2001 to 2004. The DARTS project received the financial support of the European Communities and Sustainable Growth Program (GROWTH 2000).

SAFET

SafeT is a thematic network on tunnels that was started in May 2003 and finished in April 2006. The objective of the SafeT network was to develop comprehensive guidelines for pan-European decision making on the safety of existing tunnels (primarily road, but also rail) by investigating, identifying, assessing, and proposing best practice solutions for: (1) preventing incidents/accidents in existing tunnels, and (2) mitigating its effects—for both people and goods—to ensure a high level of tunnel safety in Europe.

From the literature search and the discussions in the SafeT network it can be concluded that many different methods are used to assess safety during the design and operation of a tunnel. The applied methods vary from qualitative to quantitative, from probabilistic to deterministic (*11*).

Important for the selection of a tunnel safety assessment method is the level of detail in the available input for the method. In the early stage of tunnel design it is important that more generic methods such as checklists be applied. In the outline design, more detailed methods can be implemented. At this stage deterministic and probabilistic methods are used. In the detailed design phase, the application of risk assessment methods is important to ensure that assumptions made in earlier tunnel risk assessments are correct and that the reliability of tunnel technical systems meets the design criteria. During the operation and maintenance of the tunnel it is important to use methods that assess if the actual safety performance of the tunnel meets the tunnel safety criteria. Also important are methods that monitor possible changes in the use of the tunnel, changes in technical tunnel systems, and changes in the tunnel operation.

SIRTAKI

SIRTAKI stands for Safety Improvement in Road & Rail Tunnels using an Advanced Intensive decision support system. The strategic goal of the project was the development and assessment of an advanced decision support system that specifically tackles safety issues in tunnel management, as well as emergency handling and integration within the overall network management.

SIRTAKI aims to improve mobility management by the development of advanced surveillance and control systems focused on safety in road and railways tunnels that can be coordinated within urban and interurban traffic management systems. This in turn can perform management of large-scale events and crises, which can be supported by Inference Module and Knowledge Basis tools based on advanced modeling and simulation of emergency situations. The introduction of this system can reduce risks and enable the management of emergency situations in roads and railways, making the transport chain more efficient and safe for both passengers and freight.

SIRTAKI provides innovations in four main aspects of tunnel management and emergency situations: (1) prevention of conflicting situations and emergencies, (2) support for tunnel managers, (3) integrated management within the transport network, and (4) improvements to sensors and surveillance equipment.

The benefits from SIRTAKI project can be summarized as follows (*12*):

- Improving safety in tunnels: reducing the risk of accidents in tunnels and the severity of those that do take place.
- Reducing stress in operators and citizens who are on the frontlines of an emergency situation.
- Managing tunnels and the rest of the transport network in a coordinated way and, therefore, improving the performance of the available transport infrastructures.
- Using the integrated management of not only emergencies, but also other special situations such as congestion, maintenance works, and so forth.
- Reducing the total time of emergency analysis by 15%.

VIRTUAL FIRES

Initiated in November 2001, the Virtual Real Time Emergency Simulator, or "Virtual Fires," was a three-year project with eight partners from five European countries (*13, 14*). It was coordinated by the Institute for Structural Analysis (Austria) and the goal was to develop a simulator that helps train fire fighters in the efficient mitigation of tunnel fires, using a computer-generated virtual environment. This is a low-cost and environmentally friendly alternative to real fire fighting exercises that involve burning fuel in a disused tunnel. The simulator can also be used to test the fire safety of a tunnel and the influence of mitigating measures (ventilation, fire suppression, etc.) on its fire safety level. The end users will include tunnel operators, designers, and government regulatory authorities.

SAFE TUNNEL

The main objective of this project is to reduce the number of accidents inside road tunnels through "preventive" safety measures. The primary focus is to achieve a dramatic reduction of "fire accidents," which, although rare, are the most serious safety risks inside tunnels. The primary goal is to introduce measures capable of reducing the number of HGV incidents in the Frejus Tunnel by 40% within 10 years, with the additional objective of cutting the frequency of fires in tunnels by 50% within 6 years.

The basic ideas are:

- To increase awareness of vehicle status to avoid tunnel access to those vehicles with detected or imminent anomalies.
- To achieve tele-control surveillance of vehicle speed inside the tunnel.

Specific objectives are:

- Development of two demonstrator trucks equipped with preventive diagnosis devices, tele-control, and human machine interface (HMI) facilities.
- Development of the control center to manage Safe Tunnel applications.
- Analysis of the needs of tunnel operators for managing safety-related operations.
- Transmission of data by a public telecom network.
- Demonstrations of the Safe Tunnel concepts through field tests in Frejus Tunnel.
- Evaluation includes technical and impact analysis, user acceptance estimation, socioeconomic impact estimation, and cost–benefits analysis.
- Recommendations for standards.

Methodology:

- Develop or adapt existing on-board vehicle sensors to monitor primary vehicle functions to forecast and detect anomalies in on-board devices. This information will be transmitted to the control center and managed by the tunnel operator through a public telecommunications network.

- Develop a control center to receive and process the information transmitted by equipped HGVs or by infrastructure-based electronic systems (when the vehicles are not equipped). The preventive actions consist of access controls at the entry point.
- Develop "Tele-Control" of the equipped vehicle through automatic actuation of the recommended speed. The project will study the possibility of installing an infrastructure system inside the tunnel capable of showing a light beam, which drivers of unequipped vehicles must follow.

A thermal check system aims at identifying overheated vehicles before they enter the tunnel. This thermal gate, located before the toll station, is composed of an automatic gate with infrared sensors and a portable system for checking vehicles with anomalous heating situations.

The thermal gate performs the following operations:

- Acquisition of infrared images.
- Image processing to detect possible hot spots.
- Activation of a warning if the hot spot exceeds a threshold.
- Stops the suspect vehicles.

EUROTAP

EuroTAP is the European Tunnel Assessment Programme (*15*), a program that checks the safety of existing European tunnels. The original 1999 checklist has been enhanced regularly by following these basic rules and opinions:

- German regulations RABT 2003 (directives on the equipment and operation of road tunnels).
- Recommendations of UNECE (United Nations Economic Commission for Europe) expert group on the safety of road tunnels, December 2001.
- Opinions of PIARC (World Road Association) and CEDR (Conference of European Directors of Roads).
- EU Directive 2004/54/EC (*16*).
- National rules of the six major European tunnel states: Italy, Austria, France, Spain, the United Kingdom, and Switzerland.

By 2004, a total of 144 tunnels had been tested.

SOLIT

The Safety of Life in Tunnels (SOLIT) project was sponsored by the German government. More than 50 large-scale tests were performed. Extrapolating from free-burn data, researchers calculated that the fire load of an HGV with idle pallets could grow to 180 MW (614 MBtu/hr). Water mist systems reduced the HRR to 20 to 50 MW (68–171 MBtu/hr).

L-SURF

Large Scale Underground Research Facility on Safety and Security (L-surF) studied safety and security in enclosed underground spaces of high importance for tunnel fires, terror attacks in metros, and so forth from March 2005 to May 2008 (*17*). However, the European Union's (EU's) competence related to safety and security is largely unstructured, fragmented, and mostly national oriented. Especially missing is a large-scale research facility and the coordination and synergy of existing facilities. Within the design study for L-surF, all relevant aspects for such a facility were elaborated to a level that the facility could be established, at least as a legal entity with the necessary structures and activities. Preliminary concepts and plans for the physical construction are described. L-surF is a design study within the Sixth Framework Program of the European Community and involves the cooperation of five of Europe's leading institutions on safety and security for underground facilities in Switzerland, Sweden, Germany, the Netherlands, and France.

EGSISTES

EGSISTES, a French project funded by the National Research Agency, is a global evaluation of intrinsic safety and security for underground transport systems. It is a 3-year project dedicated to the evaluation of global security in underground infrastructures (January 2007 to January 2010). EGSISTES includes three work packages:

1. Vulnerability analysis
   - Risk analysis and
   - Accidental risk and threat.
2. Knowledge improvement and model development for consequences evaluation
   - Experimental approach (fire, explosion, gas dispersion) and
   - Numerical simulation (one-dimensional and three-dimensional numerical tools).
3. Existing tools capability evaluation.

One the most important projects at the European level is the HySafe network of excellence (*18, 19*) and projects such as HyTunnel and InsHyde, which were directly addressing the safety of hydrogen vehicles in confined spaces. In addition, a HyApproval project goal is to make a "handbook for approval of Hydrogen refueling stations" that will be used to certify public hydrogen filling stations in Europe.

The objectives of the HyTunnel project were to:

- Review tunnel regulations, standards, and practice with respect to the management of hazards and emergencies, such as the European Community directive.
- Identify appropriate accident scenarios for further investigation.

- Review previously published experimental and modeling work.
- Extend the understanding of hydrogen hazards inside tunnels by physical experiments and numerical modeling.
- Suggest guidelines for the safe introduction of hydrogen-powered vehicles into tunnels.

During the course of the project, ten experiments were performed with hydrogen and compressed natural gas (CNG), as well as benchmark exercises for the numerical simulations. The small- and large-scale tests show the various combustion regimes according to the size of the cloud (air-hydrogen) and the concentration of hydrogen in the mixture.

In addition to the results gained, the HyTunnel project has revealed needs for further research, in particular on the following topics:

- Realistic scenarios in tunnels (release downwards under the vehicle) with delayed ignition of nonuniform mixtures.
- Scientifically grounded requirements to the location and parameters of PRD.
- Impinging jet fires and conjugating heat transfer in conditions of blow down.
- Releases into congested space with Deflagration to Detonation Transition (DDT).
- Development of hydrogen safety engineering methodology and applying it to a tunnel scenario.

In general, the project improved the modeling of small releases and led to a better understanding of the hydrogen dispersion and combustion phenomena. The project delivered a 90-page document entitled *Initial Guidance for Using Hydrogen in Confined Spaces* (*19*).

SUMMARY

There are a number of recently completed and on-going projects on tunnel safety and design for tunnel fires in the United States and Europe. Each project addresses different components of design practice for tunnel fires. The findings of these projects are essential for understanding fire dynamics in tunnels and for developing prevention and protection means against tunnel fires. The most important recent U.S. projects were:

- *Prevention and Control of Highway Tunnel Fires* (FHWA-RD-83-032) (*7*).
- *Making Transportation Tunnels Safe and Secure* [*NCHRP Report 525/TCRP Report 86* (*1*)].
- International Technology Scanning Program (*Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response*) (*2*).
- National Tunnel Scan.

The most important recent international projects were:

- UPTUN
  - Development of innovative technologies. Focus was on technologies in the areas of detection and monitoring, mitigating measures, influencing human response, and protection against structural damage. The main output is a set of innovative cost-effective technologies.
  - Development, demonstration, and promotion of procedures for safety-level evaluation, including decision support models, as well as knowledge transfer. The main output was a risk-based evaluating and upgrading model.
- FIT
  - Optimized research efforts to reach critical mass and enhance the impact at the European level by combining the results of the different projects.
  - Established a set of consultable databases with essential knowledge on fire in tunnels.
  - Developed recommendations on design fires for tunnels.
  - Developed a European consensus for fire safe design on the basis of existing national regulation, guidelines, codes of practices, and safety requirements.
  - Defined best practices for tunnel authorities and fire emergency services on prevention and training, accident management, and fire emergency operations.
- DARTS—Durable and Reliable Tunnel Structures.
- SafeT—developed guidelines for the safety of existing tunnels by the prevention and mitigation of tunnel fire effects.
- SIRTAKI—Safety Improvement in Road and Rail Tunnels using an advanced intensive decision support system.
- Virtual Fires—developed a simulator that allows for the training of fire fighters in the efficient mitigation of tunnel fires, using a computer-generated virtual environment.
- Safe Tunnel with the basic goals of
  - Increasing awareness of vehicle status to avoid tunnel access to those vehicles with detected or imminent anomalies.
  - Achieving tele-control surveillance of vehicle speed inside a tunnel.
- EuroTAP—European Tunnel Assessment Programme—Inspection and testing of existing tunnels.
- SOLIT (Safety of Life in Tunnels)—with the goal of performing fire load testing and study water mist systems in tunnels.
- L-surF—Large Scale Underground Research Facility on Safety and Security.
- EGSISTES—a global evaluation of intrinsic safety and security for underground transport systems. HyTunnel and InsHyde directly address the safety of hydrogen vehicles in confined spaces.

CHAPTER THREE

TENABLE ENVIRONMENT—LITERATURE REVIEW

To understand and interpret the objectives of fire regulations it is necessary to have basic knowledge in the physics of fire, tenable limits for escaping civilians and firemen, and damage criteria for tunnel construction and equipment.

Fire produces high temperatures, heat radiation, a low concentration of oxygen, low visibility, and different lethal toxic and/or corrosive gases. All of these physical phenomena, some of which can be calculated with some accuracy, can be dangerous to people, construction, equipment, and vehicles.

The tenable environment is an environment that supports human life for a specific period of time. The goal of fire life safety systems is to provide a tenable environment for evacuation.

The current technology is capable of analyzing and evaluating each of the unique conditions of each path to provide proper ventilation for pre-identified emergency conditions. The same ventilating devices may or may not serve both normal operating conditions and pre-identified emergency requirements. The goals of the ventilation system, in addition to addressing fire and smoke emergencies, are to assist in the containment and purging of hazardous gases and aerosols, such as those that could result from a chemical or biological release. Some information, especially on heat effects, was taken from the annex material of NFPA 502 and is summarized here.

HEAT EFFECTS

Exposure to heat can threaten life in three basic ways (NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways):

1. Hyperthermia,
2. Body surface burns, and
3. Respiratory tract burns.

The following are used in the modeling of life threat owing to heat exposure in fires:

- The threshold of burning of the skin, and
- The exposure at which hyperthermia is sufficient to cause mental deterioration and thereby threaten survival.

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

The tenability limit for the exposure of skin to radiant heat is approximately 2.5 kW/m^2 (800 $Btu/hr/ft^2$). Below this incident heat flux level exposure can be tolerated for 30 min or longer without significantly affecting the time available for escape. Above this threshold value the time to burn skin resulting from radiant heat decreases rapidly according to Eq. 1.

$$t_{Irad} = 4q^{-1.36} \qquad (1)$$

where:

t_{Irad} = time to burning of skin resulting from radiant heat (minutes); and
q = radiant heat flux (kW/m^2 or $Btu/hr/ft^2$).

As with toxic gases, an exposed individual can be considered to have accumulated a dose of radiant heat over a set period of time. The fraction equivalent dose (FED) of radiant heat accumulated per minute is the reciprocal of t_{Irad}.

Radiation is created by temperature. The level of radiation depends on the temperature and the emissivity of the smoke. When the temperature within the smoke layer is not constant integration is necessary to calculate the radiation level. The radiation is produced by the fire itself and by the hot smoke layer.

Radiant heat tends to be directional, producing localized heating of particular areas of skin even though the air temperature in contact with other parts of the body might be relatively low. Skin temperature depends on the balance between the rate of heat applied to the skin surface and the removal of heat subcutaneously by the blood. Thus, there is a threshold radiant flux below which significant heating of the skin is prevented but above which rapid heating occurs.

Based on the preceding information, it is estimated that the uncertainty associated with the use of Eq. 1 is ±25%. Moreover, an irradiance of 2.5 kW/m^2 (800 $Btu/hr/ft^2$) would correspond to a source surface temperature of approximately 200°C (392°F), which most likely would be exceeded near the fire where conditions are changing rapidly. Near the fire the radiation is created by the fire itself, as well as the hot smoke. Farther from the fire it is only the smoke temperature that creates a dangerous condition. To make evacuation possible, the radiation level must be under the limit that causes severe pain on bare skin for an exposure time of several minutes: the threshold value is roughly 2 to 2.5 kW/m^2 (635 to 800 Btu/hr/ft^2). Firefighters can normally withstand a radiation level of 5 kW/m^2 (1600 Btu/hr/ft^2) for at least seven minutes because of protective clothing. Their operation time is a function of a self-contained breathing apparatus and is typically not longer than 30 min. For a firefighter to withstand a stay of 20 min, the radiation level cannot exceed 2 kW/m^2 (*20*).

The amount of time to incapacitation, when exposed to convective heat from air containing less than 10% water vapor by volume can be made by using either Eq. 2 or Eq. 3.

As with toxic gases, an exposed occupant can be considered to accumulate a dose of convected heat over a period of time. The FED of convective heat accumulated per minute is the reciprocal of t_{Iconv}.

Convective heat accumulated per minute depends on the extent to which an exposed occupant is clothed and the nature of the clothing. For fully clothed subjects, Eq. 2 is suggested:

$$t_{Iconv} = \left(4.1 \times 10^{8}\right) T^{-3.61} \qquad (2)$$

where:

t_{Iconv} = time (minutes); and
T = temperature (°C).

For unclothed or lightly clothed subjects, it might be more appropriate to use Eq. 3:

$$t_{Iconv} = \left(5.0 \times 10^{7}\right) T^{-3.4} \qquad (3)$$

where:

t_{Iconv} = time (minutes); and
T = temperature (°C).

Eqs. 2 and 3 are empirical and can be used for humans. It is estimated that the uncertainty associated with these equations is ±25%.

Thermal tolerance data for unprotected human skin suggest a limit of about 120°C (248°F) for convective heat. Within minutes of exposure above this temperature there will be an onset of considerable pain and the production of burns. Depending on the length of exposure, convective heat below this temperature can also cause hyperthermia.

The body of an exposed individual can be regarded as acquiring a "dose" of heat over a period of time. Generally, a short exposure to a high radiant heat flux or temperature is less tolerable than a longer exposure to a lower temperature or heat flux. A methodology based on additive FEDs, similar to that used with toxic gases, can be applied. Providing that the temperature in the fire is stable or increasing, the total fractional effective dose of heat acquired during an exposure can be calculated using Eq. 4.

$$FED = \sum \left(\frac{1}{t_{Irad}} + \frac{1}{t_{Iconv}} \right) \Delta t_{t_1}^{t_2} \qquad (4)$$

Note 1: In areas within occupancy where the radiant flux to the skin is under 2.5 kW/m^2 (800 Btu/hr/ft^2) the first term in Eq. 4 is to be set at zero.

Note 2: The uncertainty associated with the use of Eq. 4 would depend on the uncertainties associated with the use of the three previous equations.

The time at which the FED accumulated sum exceeds an incapacitating threshold value of 0.3 represents the time available for escape for the chosen radiant and convective heat exposures. Consider an example with the following characteristics:

1. Evacuees are lightly clothed.
2. There is zero radiant heat flux.
3. The time to FED is reduced by 25% to allow for uncertainties in Eqs. 2 and 3.
4. The exposure temperature is constant.
5. The FED is not to exceed 0.3.

Eqs. 3 and 4 can be manipulated to provide the following equation:

$$t_{\exp} = \left(1.125 \times 10^{7}\right) T^{-3.4} \qquad (5)$$

where:

$t_{\exp}$ = time of exposure to reach a FED of 0.3 (minutes).

This gives the results shown in Table 2.

AIR CARBON MONOXIDE CONTENT

Air CO tenable environment content is as follows:

- Maximum of 2,000 ppm for a few seconds.
- Averaging 1,150 ppm or less for the first 6 min of the exposure.
- Averaging 450 ppm or less for the first 15 min of the exposure.
- Averaging 225 ppm or less for the first 30 min of the exposure.
- Averaging 50 ppm or less for the remainder of the exposure.

These values need to be adjusted for altitudes above 984 m (3,000 ft).

TABLE 2
EXPOSURE TIME AND INCAPACITATION

Exposure Temperature		Maximum Exposure Time Without Incapacitation (min)
°C	°F	
80	176	3.8
75	167	4.7
70	158	6.0
65	149	7.7
60	140	10.1
55	131	13.6
50	122	18.8
45	113	26.9
40	104	40.2

Source: NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways.

TOXICITY

The toxicity of fire smoke is determined primarily by a small number of gases, which may act additively, synergically, or antagonistically (*21*). For example, the addition of the influence of CO and hydrogen cyanide (HCN) may be represented by:

$$A = \frac{[CO]}{(LC_{50}CO_{30})} + \frac{[HCN]}{(LC_{50}HCN_{30})} \tag{6}$$

where:

[ ] indicates the actual concentration;
$LC_{50}CO_{30}$ = 4,600 ppm (concentration level at which 50% of all individuals will die solely from CO after 30 min); and
$LC_{50}HCN_{30}$ = 160 ppm (concentration level at which 50% of all individuals will die solely by HCN after 30 min).
If A = 1, approximately 50% of the victims will die.

This relation has been shown to hold for concentrations of CO and HCN equal to 25%, 50%, and 75% of their respective 30-min LC_{50} values.

Eq. 6 has been termed the fractional summation approach. An easier approach considers only the maximum allowable concentration for a certain fire. Klote and Milke (*22, 23*) have presented comprehensive lethal levels for 5 min and 30 min exposure, although it is evident that different authors propose different values.

SMOKE OBSCURATION LEVELS, VISIBILITY

Smoke obscuration levels need to be continuously maintained below the point at which a sign internally illuminated at 80 lx (7.5 fc) is discernible at 30 m (100 ft), and doors and walls are discernible at 10 m (33 ft).

The properties of smoke are commonly expressed in terms of transmittance, as well as either optical density (OD) or attenuation coefficient (also called the extinction coefficient) (*21*).

The transmittance T of smoke is defined as:

$$T = I_x / I_o \tag{7}$$

where:

I_o is the intensity of light at the beginning of the path; and
I_x is the intensity of light remaining after it has passed through the path length.

The OD per unit distance δ is related to the transmittance by the following equation:

$$\delta = -\frac{(\log_{10} T)}{x} \tag{8}$$

where:

x is the distance travelled by light (the path length).

The attenuation (or extinction) coefficient per unit distance K is defined in the same way as the OD, but using Neperian logarithms:

$$K = -\frac{(\log_e T)}{X} \tag{9}$$

$$K = 2.303\delta \tag{10}$$

Sometimes the percentage obscuration λ is used and is defined as:

$$\lambda = 100(1 - T) \tag{11}$$

Eq. 8 can then be replaced by

$$\delta = \frac{\log_{10}(1 - \lambda/100)}{x} \tag{12}$$

The visibility distance V(m) can be estimated using the extinction (or attenuation) coefficient K(m^{-1}) of the air–smoke mix:

$$V = A/K \tag{13}$$

where:

A is a constant between 2 and 6 depending on the signs to be seen (reflecting or illuminated).

AIR VELOCITIES

Air velocities in the enclosed tunnel need to be greater than or equal to 0.76 m/s (150 fpm) and less than or equal to 11.0 m/s (2,200 fpm). The maximum limit is set based on the ability of people to walk in a high air speed environment (NFPA 502 Standard).

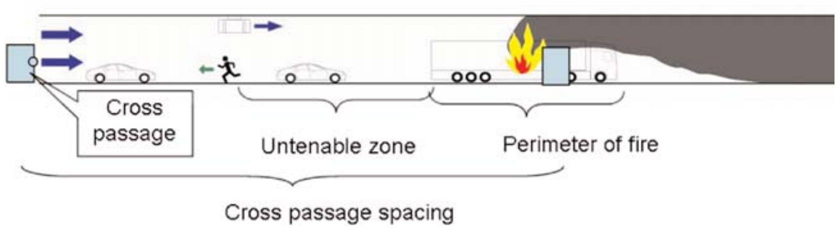

FIGURE 2 Cross passage spacing.

NOISE LEVELS

Noise levels need to be a maximum of 115 dBA for a few seconds and a maximum of 92 dBA for the remainder of the exposure (NFPA 502 Standard).

GEOMETRIC CONSIDERATIONS

Some factors that require consideration in establishing a tenable environment in evacuation paths are as follows:

- The evacuation path requires a height clear of smoke of at least 2.0 m (6.56 ft). The current precision of modeling methods is within 25%. Therefore, in modeling methods a height of at least 2.5 m (8.2 ft) needs to be maintained above any point along the surface of the evacuation pathway.
- The application of tenability criteria at the perimeter of a fire is impractical. The zone of tenability needs to be defined to apply outside a boundary away from the perimeter of the fire. This distance will depend on the FHRR and radiation, and could be as much as 30 m (100 ft) (Figure 2).

TIME CONSIDERATIONS

The project is supposed to develop a time-of-tenability criterion for evacuation paths with the approval of the authority having jurisdiction. Some factors to be considered in establishing this criterion are the time for:

- The fire to ignite and become established.
- The fire to be noticed and reported.
- The entity receiving the fire report to confirm the existence of fire and time to initiate response.
- All people who can self-rescue to evacuate to a point of safety.
- Emergency personnel to arrive at the station platform.
- Emergency personnel to search for, locate, and evacuate all those who cannot self-rescue.
- Fire fighters to begin to suppress the fire.

If a project does not establish a time-of-tenability criterion, the system is designed to maintain the tenable conditions for at least 1 h.

SUMMARY

A tenable environment, an environment that supports human life for a specific period of time, is an important criterion for the design and operation of fire life safety systems. It is well-defined by NFPA 502 and similar in most national and international standards. This prescriptive tenable environment requirement as the function of time is the basis for performance-based design of the fire life safety systems and risk analysis evaluations. For road tunnels tenable environment as a function of time is defined for:

- Heat effects in terms of temperature, humidity, and radiation;
- Concentration of CO and other gases;
- Toxicity of gases;
- Smoke obscuration level and visibility;
- Air velocities;
- Noise levels;
- Geometric considerations; and
- Time consideration.

Gaps in tenable environment are not addressed in this chapter. However, it is well known, for example, that visibility is one of the tenable environment limitations. This limitation does not allow using fixed fire suppression systems in many tunnels. Although the visibility criteria were developed for smoke and toxic gases, the question arises as to whether the same criteria should be applied to water or water mist.

CHAPTER FOUR

SIGNIFICANT FIRE INCIDENTS IN ROAD TUNNELS—LITERATURE REVIEW

Fires occur in tunnels far less frequently than in buildings. However, because of the unique nature of a tunnel fire, they are more difficult to suppress and extinguish, and usually get more attention.

In theory, the frequency of tunnel fires is related to variables such as tunnel length, traffic density, speed control, and slope of the road. Each variable has to be accounted for when comparing different tunnels.

- Urban tunnels tend to have a higher fire rate than other tunnels;
- In many tunnels no fire has occurred; and
- An event frequency span of about one fire per month to one fire per year per tunnel applies only to tunnels that are either very long, have a significant amount of traffic, or both. A large majority of tunnels report far fewer fires.

Table 3 lists many major tunnel fires, most of which resulted in injuries, loss of life, and structural damage. Although the possibility of a significant fire incident in road tunnels is low, it can still happen. This table compiled information from numerous literature sources and provides a year of fire event, tunnel location, tunnel length, duration of fire when information was available, and fire consequences in terms of deaths or injuries and damages to the structure and other property. Some major fire events are also described in web-only Appendix G.

It was reported that the probability of significant fires from HGVs is greater than from passenger cars. When HGVs are involved in fires, there is a higher risk of the fire developing into a much larger, more serious fire.

The duration of recorded serious fires in road tunnels range from 20 min to 4 days. Most of the serious fires are in the range of 2 to 3 h. However, four fires in road tunnels were particularly serious.

- Nihonzaka, Japan, collision, duration 4 days (1979).
- Mont Blanc, France/Italy, self-ignition of an HGV, duration 53 h (1999) (see Figure 3).
- Tauern, Austria, collision, duration 15 h (1999).
- Gotthard, Switzerland, collision, duration 20 h (2001).

From an analysis of the catastrophic tunnel fire events the following conclusions were derived:

- Fires developed much more quickly than expected.
- Fire temperatures of in excess of 1000°C (1832°F) have been achieved.
- Smoke volumes were higher than expected from an early stage of the fire growth.
- Fire spread between vehicles occurred over a much greater distance than previously expected (e.g., more than 200 m or 656 ft in the Mont Blanc Tunnel).
- During fires road tunnel users behaved unexpectedly, such as:
  - Did not realize the danger to which they were exposed.
  - Failed to use the safety infrastructure provided for self-rescue.
  - Incorrectly believed that they were safer in their cars than if they used the self-rescue safety systems.
  - Chose to stay in their vehicles during the early stages of a fire because they did not want to leave their property.
  - Realized too late the danger they had placed themselves in, by which time it was too late to execute self-rescue.

CAUSE OF VEHICULAR FIRES IN ROAD TUNNELS

Collisions and other vehicle accidents are not the most frequent cause of tunnel fires, although most large fires are caused by accidents. The original cause of collisions and other traffic accidents is often driver in-attention.

NTSB analysis, in conjunction with that from international studies, of the cause of bus fires show that the primary causes of such fires are:

- Engine fires, which account for approximately two-thirds of bus fires. Engine fires can be the result of damaged fuel lines, oil lines, or an overheated heating, ventilation, and air conditioning system.
- Electrical short circuits followed by a cable fire (the most frequent cause for light-weight vehicle fires). Electrical fire or cable insulation was the item first ignited in 29% of U.S. bus fires.
- Of the bus and school bus fires, 27% began with flammable or combustible liquids or gases, piping, or filters.
- Underseat heaters catching fire.
- Braking systems that can overheat (according to French statistics in 60% to 70% of fire events involving trucks).
- Collisions.
- Other defects leading to the self-ignition of a vehicle.

TABLE 3
LIST OF ROAD TUNNEL FIRES

Year	Tunnel	Country	Tunnel Length, m (ft)	Fire Duration	Damage		
					People	Vehicles	Structure
1949	Holland	United States	2550 (8,365)	4 h	66 injured	10 trucks, 13 cars	Serious
1965	Blue Mountain	United States	1300 (4,265)	—	—	1 truck	—
1967	Suzaka	Japan	244 (800)	11 h	2 injured	12 trucks	—
1968	Moorfleet	Germany	243 (800)	1 h	—	1 truck	Serious
1970	Wallace	United States	1000 (3,280)	—	—	—	Slight
1974	Mont Blanc	France/ Italy	11 600 (38,000)	15 min	1 injured	—	—
1974	Chesapeake Bay Bridge	United States	2440 (8,000)	4 h	1 injured	1 truck	—
1976	Crossing BP	France	430 (1,410)	1 h	12 injured	1 truck	Serious
1978	Velsen	Netherlands	770 (2,530)	1 h 20 min	5 dead 5 injured	4 trucks, 2 cars	Serious
1979	Nihonzaka	Japan	2045 (6,700)	159 h	7 dead 2 injured	127 trucks, 46 cars	Serious
1980	Kajiwara	Japan	740 (2,427)	1.5 h	1 dead	2 trucks	Serious
1982	Caldecott	United States	1028 (3,372)	2 h 40 min	7 dead 2 injured	3 trucks, 1 bus, 4 cars	Serious
1982	Lafontaine	Canada	1390 (4,565)		1 dead	1 truck	Limited
1983	Pecorila Galleria	Italy	662 (2,170)	—	9 dead 22 injured	10 cars	Limited
1986	L'Arme	France	1105 (3,625)	—	3 dead 5 injured	1 truck, 4 cars	Limited
1987	Gumefens	Switzerland	343 (1,125)	2 h	2 dead	2 trucks, 1 van	Slight
1989	Brenner	Austria	412 (1,350)		2 dead 5 injured		
1990	Røldal	Norway	4656 (15,270)	50 min	1 injured	—	Limited
1990	Mont Blanc	France/ Italy	11 600 (38,000)	—	2 injured	1 truck	Limited
1993	Serra Ripoli	Italy	442 (1,450)	2 h 30 min	4 dead 4 injured	5 trucks 11 cars	Limited
1993	Hovden	Norway	1290 (4,230)	1 h	5 injured	1 motor cycle, 2 cars	Limited
1994	Huguenot	South Africa	3914 (12,840)	1 h	1 dead 28 injured	1 bus	Serious
1995	Pfander	Austria	6719 (22,040)	1 h	3 dead 4 injured	1 truck, 1 van, 1 car	Serious
1996	Isola delle Femmine	Italy	148 (485)	—	5 dead 20 injured	1 tanker, 1 bus, 18 cars	Serious
1999	Mont Blanc	France/ Italy	11 600 (38,000)	2.2 days	39 dead	23 trucks, 10 cars, 1 motorcycle, 2 fire engines	Serious (closed for 3 years)
1999	Tauern	Austria	6401 (21,000)	15 h	12 dead 49 injured	14 trucks, 26 cars	Serious (closed for 3 months)
2000	Seljestad	Norway	1272 (4,173)	45 min	6 injured	1 truck, 4 cars, 1 MC	—

(*continued on next page*)

TABLE 3
(*continued*)

Year	Tunnel	Country	Tunnel Length, m (ft)	Fire Duration	Damage		
					People	Vehicles	Structure
2001	Prapontin	Italy	4409 (14,463)	—	19 injured	1 truck	Serious
2001	Gleinalm	Austria	8320 (27,293)	—	5 dead 4 injured	—	—
2001	Ville Marie Tunnel	Canada	8400 (27,560)				
2001	Guldborg-sund	Denmark	460 (1,509)	—	5 dead 6 injured		
2001	St. Gottard	Switzerland	16 900 (55,450)	Over 2 days	11 dead	2 trucks, 23 vehicles	Serious
2002	Tauern	Austria	6401 (21,000)	—	1 dead	—	—
2002	A86	France	618 (2,028)	6 hr	2 dead	1 car, 1 motorcycle	—
2002	Ted Williams	United States	2600 (8,530)			1 bus	—
2002	Homer	New Zealand	—		3 injured	1 bus	—
2003	Locica	Slovenia	800 (2,625)			1 truck, 1 car	—
2003	Fløyfjell	Norway	3100 (10,171)	~10 min	1 dead	1 car	Limited
2003	Golovec	Slovenia	700 (2,297)	—	—	1 bus	
2003	Baregg	Switzerland	1390 (4,560)	—	2 dead 21 injured	4 trucks, 3 fire engines	Serious
2004	Baregg	Switzerland	1080 (3,543)	—	1 dead , 1 Injured	1 truck, 1 car	Serious
2004	Dullin	France	1500 (4,921)	—	—	1 bus	
2004	Kinkem-pois	Belgium	600 (1,969)	—	—	1 truck	Slight
2004	Frejus	France/ Italy	12 900 (42,323)	—	—	1 truck	—
2005	Frejus	France/ Italy	12 900 (42,323)	6 h Diesel leakage in HGV loaded with tires	2 dead; 21 treated for smoke inhalation	4 HGV, 3 fire fighting vehicles 1. load: Tires 2. load cheese 3. load: scrap 4. load: glue	Serious damage, tunnel closed
2006	Viamala	Switzerland	760 (2,493)		9 dead 6 injured	1 bus, 2 cars	
2006	Crap-Teig	Switzerland	2171 (7,122)			1 HGV with wooden pallets	Limited structural, electrical damage
2007	Burnley	Australia	2900 (9,514)		3 dead	4 HGVs, 7 cars	Slight
2007	Caldecott	United States, Canada	1028 (3,372)			1 car	
2007	Santa Clarita I-5 [25]	United States, Canada	165 (544)		3 dead 23 injured	33 tractor/ semi-trailer; 1 car	
2007	San Martino	Italy		>45 min	2 dead; 10 injured	1 HGV	
2009	Eiksund	Norway	7700 (25,262)		5 dead	1 HGV, 1 car	
2009	Gubrist	Switzerland			4 injured	2 cars	
2010	Trojane	Slovenia	885 (2,900)		5 injured	1 HGV	
2010	Wuxi Lihu	China			24 dead, 19 injured	1 shuttle bus	

Collected from numerous sources: *ASHRAE Handbook* (22).

FIGURE 3 Mont Blanc Tunnel after fire.

FIGURE 4 Burnley Tunnel (Australia) after fire.

Other causes that were mentioned but occur far less frequently included technical defects (self-ignition) in tunnel equipment and maintenance work in tunnels.

FREQUENCIES OF TUNNEL FIRES

In a French study representing 400 million kilometers (approximately 250 million miles) run by trucks underground, HGV fires in 26 tunnels were analyzed and roughly classified according to their importance to tunnel environment (Table 4) (*21*). The heat release for fires classified as causing some damage to the tunnel is estimated to be below 20 MW (68 MBtu/hr); serious fires are considered with heat release of more than 20 MW (68 MBtu/hr). Therefore, major fires are rare events, even in relation to the entire number of truck fires in tunnels (see Figure 4). German and Swiss data showed that only about 1 of 100 to 500 breakdowns is accompanied by a fire, with fire involved in about 1 of 10 to 20 accidents. Note that this information is currently being revisited by PIARC to reflect the latest fire events.

The risk of a vehicle fire tends to increase in situations of intensified motor heating (steep uphill lanes of tunnels, tunnels after a long uphill slope) and intensified brake heating (long downward slopes). Also, for a short period of time during the opening of a new tunnel, there can be a tendency for more fire events as was observed in the Elb Tunnel in Germany. As the drivers become more familiar with a tunnel environment, the fire rate will stabilize at a lower level.

CONSEQUENCES OF TUNNEL FIRES

Fires generally produce heat, smoke, and toxic products, which can cause damage and loss of life. Heat is the cause of damage to structure and installations, whereas it is rarely the original cause of death. The threat to humans is primarily the loss of visibility owing to smoke (which impedes evacuation), then toxicity. A secondary risk is that fires potentially represent a hazard to the environment caused by the toxicity of the smoke and substances in the drainage. The main consequences of fires are:

1. Fatalities and injuries to:
   - Tunnel users,
   - Operating personnel, and
   - Rescue forces.

   Heat, smoke, gases, lack of oxygen, and loss of visibility lead to intoxication, suffocation, burns, and even death.

TABLE 4
ESTIMATION OF FIRE RATES IN FRENCH TUNNELS

Classification of Fire		Cases of Fire for 10^8 veh x km (approx. 10^8 veh x miles)
Passenger Cars	Fires of any importance	1–2 (1.6–3.2)
Trucks Without Dangerous Goods	Fires of any importance	8 (12.9)
	Fires with some damage to the tunnel	1 (1.6)
	Very serious fires	Estimation 0.1 to 0.3 (0.16 to 0.48)
Trucks Transporting Dangerous Goods	Fires of any importance	Estimation 2 (3.2)
	Fires with involvement of the dangerous goods	Estimation 0.3 (0.48)

Source: PIARC (*21*).

2. Economic losses related to vehicles and goods, and the cost of repair of damage/reconstruction:
   - Destroying tunnel equipment (e.g., lighting, ventilation, and telecommunication);
   - Damage to the tunnel construction: the main effects are spalling of concrete, overheating of concrete reinforcement, collapse of false ceilings, and ventilation ducts; and
   - Severe damage or loss of burning vehicles and their goods.
3. Traffic disturbance resulting from closure or reduced service level of the tunnel after a fire (e.g., re-routing resulting in extra transport time, direct economic losses, and possibly increased risk to the users).
4. Potential environmental damage from the fire.

In some cases, tunnel rehabilitation after fires can take weeks or months. During this time, traffic congestion on the roads in the vicinity of the closed tunnel is an almost inevitable result, especially in densely populated areas.

In two French tunnels in Lyon (Tunnel Fourviere and Tunnel La Croix Rousse) about 40% of the fires were extinguished by a fire extinguisher (six cases). In about 60% of the events (eight cases) the help of a fire department was needed.

Most fatalities in road tunnels appear to arise from ordinary traffic accidents. Norwegian data indicated that approximately two-thirds of deaths resulted from common traffic accidents and about one-third from fire-related incidents. In addition, it stated that “dangerous goods” incidents are likely to involve fire, which may be assumed to be about one-third of fire-related incidents (see Table 5).

Fire statistics indicate that highway tunnels are safer than open roads. As far as can be determined, there have been only three major tunnel fires in the United States. Small automobile fires are frequent and occur as often as weekly in congested urban tunnels. To date, such fires have been extinguished without difficulty.

SUMMARY

Although major fires in tunnels (with a HRR of more than 20 MW resulting in injuries, loss of life, and structural damage) are very rare events, because of the unique nature of a tunnel fire, they are difficult to suppress and extinguish and usually receive more attention. Fire statistics indicate that highway tunnels are safer than open roads.

When HGVs are involved in fires, there is a higher risk of the fire developing into a much larger, serious fire.

The duration of recorded serious fires in road tunnels ranged from 20 min to 4 days. Most of the serious fires last from 2 to 3 h.

Analysis of the catastrophic tunnel fire events provided the following conclusions:

- Fires develop much more quickly than expected.
- Fire temperatures in excess of 1000°C (1832°F) are achieved.
- Smoke volumes are higher than expected from an early stage of the fire growth.
- Fire spread between vehicles occurs over a much greater distance than had been expected previously.
- The road tunnel users behaved unexpectedly, such as:
  - Did not realize the danger to which they were exposed.
  - Failed to use the safety infrastructure provided for self-rescue.
  - Wrongfully believed that they were safer in their cars than if they used the self-rescue safety systems.
  - Chose to stay in their vehicles during the early stages of a fire since they did not want to leave their property.
  - Realized too late the danger they had placed themselves in, by which time it was too late to execute self-rescue.

Collisions and other vehicle accidents are not the most frequent cause of fires, although most large fires are caused by accidents.

- Engine fires cause approximately two-thirds of bus fires. They can be the result of damaged fuel lines, oil lines, or overheated HVAC systems.
- Electrical short-circuits, followed by a cable fire (the most frequent cause for light vehicle fires). Electrical fire or cable insulation was the item first ignited in 29% of the U.S. bus fires.
- Twenty-seven percent of the bus and school bus fires began with the flammable or combustible liquids or gases, piping, or filters.

TABLE 5
LIFE LOSS IN ROAD TUNNEL INCIDENTS IN OSLO

Type of Incident	Potential Loss of Life per Billion Person-Kilometers (person-miles)	Percentage
Common Traffic Accidents	0.74 (1.19)	67
Fire, Light Vehicle	0.08 (0.13)	7
Fire, Heavy Vehicle	0.24 (0.39)	21
Fire in Tunnel Installations	0.01 (0.02)	1
Dan gerous Goods” Incidents	0.04 (0.06)	4
Total	1.1 (1.77)	100

Source: *Assessment of the Safety of Tunnels Study* (*23*).

- Underseat heaters catching fire.
- Braking systems; these can overheat.
- Collisions.
- Technical defects (self-ignition) of tunnel equipment.
- Maintenance work in tunnels.

The risk of a vehicle fire tends to increase in situations of intensified motor heating (steep uphill lanes of tunnels, tunnels after a long uphill slope) and intensified brake heating (long downward slopes).

The main consequences of fires are:

1. Fatalities and injuries to
   - Tunnel users,
   - Operating personnel, and
   - Rescue forces.
2. Economic losses related to vehicles and goods and cost of repair of damage/reconstruction:
   - Destroying tunnel equipment (e.g., lighting, ventilation, and telecommunications);
   - Damage to the tunnel construction: primary effects are spalling of concrete, overheating of concrete reinforcement, and collapse of false ceilings and ventilation ducts; and
   - Severe damage or loss of the burning vehicles and their goods.
3. Traffic disturbance owing to closure or reduced service level of the tunnel after fire.
4. Potential environmental damage resulting from the fire.

In some cases, tunnel rehabilitation after fires can take weeks or months.

CHAPTER FIVE

COMBINED-USE ROAD TUNNELS—LITERATURE REVIEW

Every tunnel is unique. This chapter shows how complex tunnels can be. Considering the significant cost of tunnel construction, there is a reasonable attempt to use tunnels for different purposes.

The combined-use road tunnels can be classified as follows:

- Combined use for road vehicles and pedestrians and bicycle riders.
- Combined use for road vehicles and utilities, including gas fuel and electrical power lines.
- Combined use for road and railway vehicles.
- Railway tunnels with railway cars that carry road vehicles. A channel tunnel is an example. This type of tunnel is considered a railway tunnel and is not covered by this report.

COMBINED USE FOR ROAD VEHICLES AND PEDESTRIANS

Tunnels for combined use can be classified as follows:

- Tunnels with pedestrian walkways and bicycle lanes. The Stockton Street Tunnel in San Francisco is an example of this type of tunnel (see Figure 5). Most of these tunnels are relatively short. Such tunnels require special attention for air quality and security. Some road tunnels allow for animals to pass through under supervision.
- Tunnels that accommodate bus stops (see Figure 6). Passengers occupy the Stop area only and do not travel along the tunnel. This bus tunnel in Seattle is an example. Since 2009, a downtown Seattle Transit Tunnel has allowed bus and rail. There are many regular road tunnels that allow for any traffic and accommodate bus stops leading to the outside. Those tunnels may require special attention to public safety as they are similar to railway and metro tunnels dealing with higher concentrations of people in the tunnel. However, this could be more dangerous from a fire standpoint owing to the possibility of truck fires.

COMBINED USE FOR ROAD VEHICLES AND UTILITIES

Combined tunnels for road vehicles and utilities can include gas and fuel lines. These types of tunnels cross rivers and connect islands and even possibly continents. When finished, the Bering Straight Tunnel will contain a highway, railway, oil pipelines, and fiber optic cables. The installation of oil pipelines could lead to additional risk that would need to be addressed when designing for a fire.

COMBINED USE FOR ROAD AND RAILWAY VEHICLES

There are many examples of combined use for road and railway vehicles in tunnels (see Figure 7). Some tunnels have separate tubes for road traffic and separated tubes for railway traffic. Some of them have a single tube that serves for both road and railway traffic. An example of this is the Whittier Tunnel in Alaska. This 4-km (2.5-mile)-long, one-lane tunnel was designed as a combination highway and railway tunnel that allows cars and trains to take turns traversing the tunnel. It is the longest combined rail–highway use tunnel in North America.

Drogden Tunnel between Copenhagen in Denmark and Malmo in Sweden is an example of the combined-use tunnel with separate tubes for road and railway vehicles (*24*). It is an immersed tunnel approximately 4 km (2.5 miles) long. Completed in 2000, it consists of two uni-directional rail tunnels and two uni-directional road tunnels. All four tunnels are parallel. Between the two road tunnels there is a very narrow tunnel, or "central gallery," which runs the length of the tunnels. The central gallery consists of three smaller "galleries," one on top of the other. At the top is a "service gallery," below that is an "escape gallery," and below that is a small gallery for fire mains and drainage pipes (see Figure 8). There are cross-passages between the road tunnels and the narrow tunnel. Incidents occurred in these links in 2000, 2001, 2004 and 2007, but none in the tunnel itself. There is presently no available information on tunnel fires occurring in combined-use tunnels.

FIGURE 5 Tunnel with pedestrian walkways all along the tunnel for pedestrian crossings (San Francisco).

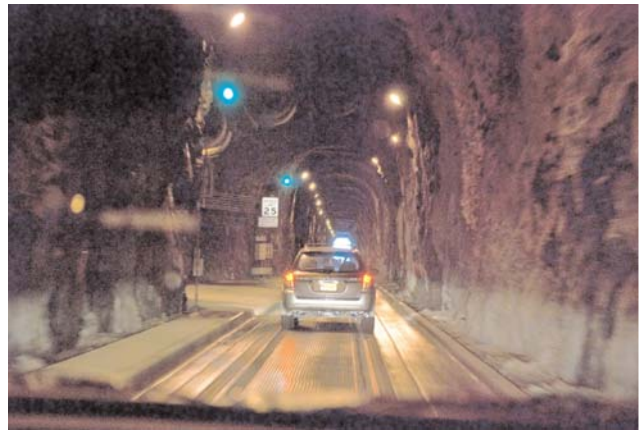

FIGURE 7 Whittier Tunnel interior: combined-use for road and railway vehicles.

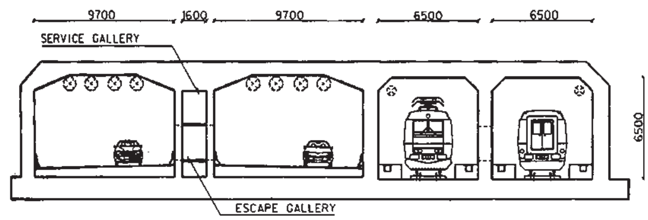

FIGURE 8 Cross section of the Drogden Tunnel (dimensions in millimeters).

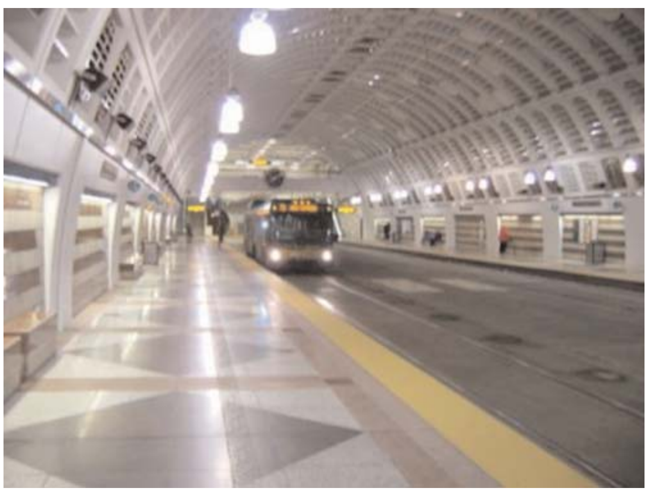

FIGURE 6 Tunnels that accommodate bus stops (Seattle).

CHAPTER SIX

FIRE TESTS—LITERATURE REVIEW

Fire tests are of vital importance in the understanding of the physics of tunnel fires, understanding the impacts of fires, and for verifying calculations, assumptions, computer models, and tunnel design. They are also important for tunnel operators and emergency responders in their efforts to coordinate and verify in practice the emergency response plans.

The fire tests that have been performed can be classified as:

- Tests before the design to develop design methodology.
- Tests during the design to verify assumptions and computer models.
- Tests during commissioning to verify the design and equipment operation.
- Tests for training purposes.
- Other tests as needed.

Important work has been conducted at full-scale (large-scale) tunnels, including:

- EUREKA tests
- Memorial Tunnel Fire Ventilation Test Program
- Runehamar Tunnel fire tests
- Full-scale tests in Norway
- Tests in Japan.

Experimental tests and especially their replications are expensive and there is a lack of willingness to carry them out. However, it is very important to perform tunnel fire tests and there is a need for multi-agency and international collaboration.

FULL-SCALE TESTS

Full-scale tests are often expensive to carry out. They require access to a tunnel or to a full-scale mock-up with some basic installations. Large-scale and full-scale fire tests with HRRs of 100 MW (341 MBtu/hr) or more require normal modifications and protection of the lining and installations. Measuring the fire size (in terms of the HRR) needs advanced instrumentation and data analysis. Some lessons learned during the previous large-scale tests included:

- Lack of control of the conditions of the experiments (e.g., humidity).
- Lack of careful design of the experiment (location of thermocouples and other instrumentation).
- Measurement errors (e.g., low-velocity measurement by inappropriate instrumentation).
- Raw data processing algorithms and subjective judgments (e.g., visibility judgments based on video recording).

Each full-scale program had its own objectives and goals, which drove methodology and resultant conclusions, making it difficult to generalize findings from the historical test data results.

There is a great need for more large-scale testing to be able to better understand the fire and smoke dynamics. However, the tests must be carefully designed and equipped with appropriate instrumentation.

Research programs using full-scale facilities generally deal with numerous but very specific aspects of safety characterized by high human and economic stakes. They require significant financial support. The main large-scale test programs that have been performed follow.

Ofenegg Tunnel Tests

To gain at least a general impression of the temperature conditions and the amount of smoke to be expected from a gasoline fire, evaluations of the performance of the fixed fire suppression system tests were performed in the Swiss Ofenegg Tunnel and in the Zwenberg Tunnel in Austria. Both test facilities were abandoned railroad tunnels.

Two types of ventilation systems, longitudinal and semi-transverse supply, were evaluated. The tunnels had *no exhaust provisions.* Sprinklers were mounted over the fuel basin and their effectiveness was evaluated. Eight tests were scheduled with different ventilation systems:

- Natural
- Longitudinal
- Semi-transversely
- With sprinklers for 500 L (132 gal.) fuel fire
- With sprinklers for 1,000 L (264 gal.) fuel fire.

Test results raised doubt of the effectiveness of sprinklers in containing a fire or in limiting the range and severity of damage. A delay in activation may produce a significant volume of high temperature steam as dangerous as the combustion products. If all ignition sources cannot be extinguished and the site uniformly cooled below a safe temperature the fire may reignite, perhaps explosively, when the sprinklers are shut off. Meanwhile, unburned vapors spread throughout the tunnel and ventilation ducts are at great hazard far from the fire, even if the fire is extinguished. (Additional test descriptions can be found in web-only Appendix E.)

Zwenberg Tunnel Tests

This program was initiated in 1975 in connection with two major motorways projects in Austria (*21*). Longitudinal and semi-transverse ventilation systems were tested. The tests included a total of 30 pool fires. (See web-only Appendix E for additional information on the tests.)

Because the test results so strongly supported the benefits of a fully transverse system running in a full extraction mode during a fire, the investigators made the following recommendations for the design and operation of a tunnel ventilation system:

- The very rapid development of a fire requires a suitable pattern of ventilation for creating the best possible conditions for rescue.
- To fulfill this requirement it is necessary
  - that the fire is quickly detected and the alarm transmitted to a tunnel control center where the operating pattern can be selected, and
  - that the appropriate technical and organizational measures be prepared, securing a fast and correct selection of the operating pattern of the ventilation system in the case of a fire.
- The tunnel must be equipped with a quickly responding fire warning system. Signals are to be transmitted with minimal possible delay to the control center.
- The primary goal must be to prevent the spread of hot fumes and smoke in the traffic space.
- This recommendation must be implemented without any restriction in all tunnels with two-way traffic.

Public Works Research Institute Experiments

PWRI experiments (*21*) (Japan 1980) are described in web-only Appendix E. The PWRI test report concluded that:

- Smoke can be kept within the minimum space and be extracted quickly if the kinetic energy of the smoke flow produced by the thermal energy of fire is less than the energy of ventilating air blowing along the tunnel toward the smoke ventilation dampers when the fans are run in reverse direction. This is achieved by the relationship between the scale of the fire and the capacity of the fans (i.e., if the fire is too big, the fans will not extract all of the smoke).
- Ventilation fans are generally designed for the purpose of reducing the concentration of exhaust gases from vehicles and extending the visible distance by taking into consideration estimated traffic volume, tunnel length, natural ventilation, ventilation by movement of vehicles, and so forth. Depending on these design conditions, there may be a small number of cases in which smoke can be reasonably extracted by existing ventilation systems.
- Stratification of smoke was partially destroyed by longitudinal ventilation at 1 m/s (197 fpm) and totally destroyed by longitudinal ventilation at 2 m/s (394 fpm).
- For determining the capacity of ventilating fans in the future, the fire smoke exhaust capacity of the fans shall be designed to meet the scale of a real vehicle fire.
- The sprinklers had an adverse effect on the tunnel environment by causing a reduction in smoke density near the ceiling and an increase in smoke density in the lower part of the tunnel.
- None of the car, bus, or pool fires was totally extinguished by the sprinklers; however, the heat generation speed was reduced in each case.

Repparfjord Tunnel Tests

Tests were undertaken at the Repparfjord Tunnel near Hammerfest, Norway from 1990 to 1992 (*21*). That test report concluded that:

- The influence of damage both to the vehicles and tunnel lining, especially in the crow area, depends on the type of vehicle. The roofs of those vehicles constructed of steel resisted the heat, whereas the roofs of the vehicles made of aluminum were completely destroyed during an early stage of the fire.
- The temperatures during most of the vehicle fires reached maximum values of 800°C to 900°C (1472°F to 1652°F). The temperatures during the HGV test reached 1300°C (2372°F). Temperatures decreased substantially within a short distance from each fire location and were greater downwind than upwind.
- The HGV burned at an HRR of more than 100 MW (341 MBtu/hr).
- Fast fire development registered in the first 10 to 15 min. Growth rates of vehicle fires vary from medium to ultrafast.
- Longitudinal ventilation destroyed stratification downwind of the HGV fire.

Benelux Tunnel Tests

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

Memorial Tunnel Tests

The Memorial Tunnel tests (United States, 1993–1995) (*21, 25, 26*) were financed by the FHWA 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. Approximately 90 tests were done with diesel oil pool fires. The obtained HRRs varied from 10 MW (34 MBtu/hr) for a 4.5 m^2 (48.4 ft^2) area to 100 MW (341 MBtu/hr) for a 44.4 m^2 (478 ft^2) area. There were 1,450 devices installed in the tunnel, providing about 4 millions points of data per experiment. (See web-only Appendix E for test facility description.)

The Memorial Tunnel program performed tests with fire sizes of 10, 20, 50, and 100 MW (34, 68, 172, and 341 MBtu/hr). The tests were done 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.

Longitudinal Tunnel Ventilation Systems

A longitudinal ventilation system employing jet fans is highly effective in managing the direction of the spread of smoke for fire sizes of up to 100 MW in a 3.2% 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 fire
- 332°C (630°F)—50 MW fire
- 677°C (1250°F)—100 MW fire.

Air velocities of 2.54 m/s to 2.95 m/s (500 fpm to 580 fpm) were sufficient to preclude the backlayering of smoke in the Memorial Tunnel for fire tests ranging in size from 10 MW to 100 MW.

Single-Zone Transverse Ventilation Systems

Single-zone, balanced, full-transverse ventilation systems that were operated at 0.155 m^3/s/lane-meter (100 ft^3/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, because there is no control over the airflow direction.

Multiple-Zone Transverse Ventilation Systems

The two-zone (multi-zone) transverse ventilation system that was tested in the Memorial Tunnel Fire Ventilation Test Program provided control over the direction and magnitude of the longitudinal airflow. Airflow rates of 0.155 m^3/s/lane-meter (100 ft^3/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 (1,600 ft to 1,900 ft) during the initial 2 min 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.

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 1,200 ft) along the arched tunnel roof before cooling and descending toward the roadway. The restriction to visibility caused by the movement of smoke occurs more quickly than does a temperature that is high enough to be debilitating. In all tests, exposure to high levels of CO was never more critical than smoke or temperature.

The effectiveness of the foam suppression system Aqueous Film-Forming Foam (AFFF) that was tested was not diminished by high-velocity longitudinal airflow [4 m/s (787 fpm)]. The time taken for the suppression system to extinguish the fire, with the nozzles located at the ceiling, ranged from 5 s to 75 s.

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:

1. 107°C (225°F)—20 MW (68 MBtu/hr) fire
2. 124°C (255°F)—50 MW (171 MBtu/hr) fire
3. 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 showed that balanced full-transverse ventilation is ineffective in controlling smoke and temperatures when fires are above 20 MW (68 MBtu/hr). Being able to effectively control the temperature when fires are below 20 MW (68 MBtu/hr) depends on their locations. 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.

Runehamar Tunnel Tests

The Runehamar Tunnel fire tests were initiated, planned, and performed by the Swedish National Testing and Research Institute from 2001 to 2003 as a part of the Swedish National Research program and in collaboration with the European UPTUN project led by TNO (The Netherlands) (*27*). (See web-only Appendix E for tests description.)

Free-burn fire tests in the Runehamar Tunnel in Norway alarmed the industry with a 200 MW (682 MBtu/hr) HGV fire size and its fast growth, because in the past no one believed in such high values. This led to a change in design HRRs for tunnel fires. In 2008, a third series of tests were run in the Runehamar Tunnel to evaluate the performance of water mist. With ventilation of up to 5 m/s (984 fpm), the water mist system was applied to a 100 m^2 (1,076 ft^2) diesel pool fire and a 200 MW (682 MBtu/hr) HGV fire. Within a minute, the diesel fire was extinguished. After a minute for the HGV fire, the temperature had dropped below 50°C (122°F), 20 m (66 ft) upstream, and below 280°C (536°F), 5 m (16 ft) downstream. A mock-up of a partially filled liquefied petroleum gas (LPG) tank was tested for exposure and boiling liquid expanding vapor explosion (BLEVE) risk.

The water mist system prevented a risk of a BLEVE for the diesel pool fire and for the solid fire if the water mist system was activated before the HRR exceeded 50 MW (171 MBtu/hr). However, if the water mist system activation was delayed until the HRR reached 200 MW (682 MBtu/hr) there was a serious risk of a BLEVE. Measurements were taken of the temperature, CO concentration, and visibility downstream of the fires. It was concluded that tenability was regained within a few minutes of activation of the water mist system.

There have been numerous papers discussing and analyzing the test results and what allowed the fire to grow to that size. Some questions included:

- The type of truck burning (open trucks are not used in the United States).
- The tunnel size, which was smaller (narrower) than a typical road tunnel.
- Protection of tunnel walls with heat protection material, which does not allow for heat dissipation through the walls, but rather reflects heat from the walls back to the tunnel environment with superimposed heat waves.

Results of the tests have been published in the Annex materials of NFPA 502, in ASHRAE, and in other documents impacting mechanical and structural tunnel design in many countries of the world.

UPTUN Project Tunnel Tests

The HRRs for single passenger cars (small and large) vary from 1.5 to 9 MW (5.1 to 31 MBtu/hr); however, the majority of the tests show HRR values of less than 5 MW (17 MBtu/hr). When two cars are involved, the peak HRR varies between 3.5 and 10 MW (12 and 34 MBtu/hr). There is a substantial variety in the time to reach peak HRR; that is, between 10 and 55 min. It has been shown that the peak HRR increases linearly with the total calorific value of the passenger cars involved in the fire. An analysis of all data available shows that the average increase is about 0.7–0.9 MW/GJ (2.4–3.1 MBtu/hr/GJ).

There have only been a few bus fire tests performed. The two tests shown in the Table 6 indicate that the peak HRR is on the order of 30 MW (102 MBtu/hr) and the time to reach peak HRR is less than ten minutes.

The highest peak HRRs were obtained for the HGV trailers (single), which were found to be in the range of 13 to 202 MW (44 to 689 MBtu/hr), depending on the fire load. The time to reach peak HRR was in the range of 10 to 20 min. The fire duration was less than one hour for all the HGV trailer tests presented in Table 6. The fire growth rate after reaching 5 MW (17 MBtu/hr) was nearly linear during all the tests carried out

TABLE 6
LARGE-SCALE EXPERIMENTAL DATA RESULTS FROM UPTUN TESTS

Type of vehicle, model year, test nr. u = longitudinal ventilation m/s	Calorific Value (GJ)	Peak HRR (Q_{max}) MW	Time to Peak HRR (min)	Peak Temperatures in Tunnel Ceiling (°C)	Reference [see Ingason (*28*)]
Passenger cars					
Ford Taurus 1.6, late 70s, Test 1	4	1.5	12	N/A	Mangs and Keski-Rahkonen
Datsun 160 J Sedan, Late 70s, Test 2	4	1.8	10	N/A	Mangs and Keski-Rahkonen
Datsun 180 B Sedan, Late 70s, Test 3	4	2	14	N/A	Mangs and Keski-Rahkonen
Fiat 127, Late 70s, 0.1 m/s	N/A	3.6	12	N/A	Ingason et al.
Renault Espace J11-II, 1988, Test 20, u = 0.5 m/s	7	6	8	480	Steinert
Citroën BX, 1986	5	4.3	15	N/A	Ship and Spearpoint
Austin Maestro, 1982	4	8.5	16	N/A	Ship and Spearpoint
Opel Kadett, 1990, Test 6, u = 1.5 m/s	N/A	4.9	11	210	Lemaire et al.
Opel Kadett, 1990, Test 7, u = 6 m/s	N/A	4.8	38	110	Lemaire et al.
Renault 5, 80s, Test 3	2.1	3.5	10	N/A	Joyeux
Renault 18, 80s, Test 4	3.1	2.1	29	N/A	Joyeux
Small Car, 1995, Test 8	4.1	4.1	26	N/A	Joyeux
Large Car, 1995, Test 7	6.7	8.3	25	N/A	Joyeux
Trabant, Test 1	3.1	3.7	11	N/A	Steinert
Austin, Test 2	3.2	1.7	27	N/A	Steinert
Citroen, Test 3	8	4.6	17	N/A	Steinert
Renault Laguna, 1999	13.7	8.9	10	N/A	Marlair and Lemaire
Two passenger cars					
Citroen BX + Peugeot 305, 80s, Test 6	8.5	1.7	N/A	N/A	Joyeux
Small Car + Large Car, Test 9	7.9	7.5	13	N/A	Joyeux
Large Car + Small Car, Test 10	8.4	8.3	N/A	N/A	Joyeux
BMW + Renault 5, 80s, Test 5	N/A	10	N/A	N/A	Joyeux
Polo + Trabant, Test 6	5.4	5.6	29	N/A	Steinert
Peugeot + Trabant, Test 5	5.6	6.2	40	N/A	Steinert
Citroen + Trabant, Test 7	7.7	7.1	20	N/A	Steinert
Jetta + Ascona, Test 8	10	8.4	55	N/A	Steinert
Three passenger cars					
Gold + Trabant + Fiesta, Test 4	N/A	8.9	33	N/A	
Buses					
A 25–35-year-old, 12-m long Volvo School Bus with 40 Seats, EUREKA 499, u = 0.3 m/s	41	29	8	800	Ingason
A Bus Test in the Shimizu Tunnel, u = 3–4 m/s	N/A	30	7	303	Kunikane et al.
HGV					
A Trailer Load with Total 10.9 Ton Wood (82%) and Plastic Pallets (18%). Runehamar Test Series, Test 1, u = 3 m/s	240	202	18	1365	Ingason and Lŏnnermark
A Trailer Load with Total 6.8 Ton Wood Pallets (82%) and PUR Mattresses (18%). Runehamar Test Series, Test 2, u = 3 m/s	129	157	14	1282	Ingason and Lŏnnermark
A Leyland DAF 310ATi: HGV Trailer with 2 Tons of Furniture, EUREKA 499, u = 3–6 m/s	87	128	18	970	Grant and Drysdale
A Trailer with 8.5 Ton Furniture, Fixtures, and Rubber Tires. Runehamar Test Series, Test 3, u = 3 m/s	152	119	10	1281	Ingason and Lŏnnermark
A Trailer Mock-up with 3.1 Ton Corrugated Paper Cartons Filled with Plastic Cups (19%), Runehamar Test Series, Test 4, u = 3 m/s	67	67	14	1305	Ingason and Lŏnnermark

(*continued on next page*)

TABLE 6
(*continued*)

Type of vehicle, model year, test nr. u = longitudinal ventilation m/s	Calorific Value (GJ)	Peak HRR (Q_{max}) MW	Time to Peak HRR (min)	Peak Temperatures in Tunnel Ceiling (°C)	Reference [see Ingason (*28*)]
HGV					
A Trailer Load with 72 Wood Pallets. Second Benelux Tests, Test 14, u = 1–2 m/s	19	26	12	600	Lemaire et al.
A Trailer Load with 36 Wood Pallets. Second Benelux Tests, Tests 8, 9 and 10, u = 1.5, 5.3, and 5 m/s	10	13, 19 and 16	16, 8, and 8	400, 290, 300	Lemaire et. al.
A Simulated Truck Load (STL), EUREKA 499	63	17	15	400	Ingason

Source: Ingason (*28*).
N/A = not available.

in the Runehamar Tunnel and it varied between 16.4 and 26.3 MW/min (55.9 and 89.7 MBtu/hr/min).

The measured ceiling temperatures varied from 110°C to 1365°C (230°F to 2489°F). These temperatures can be compared with standardized time–temperature curves for load-bearing design in buildings and underground construction. After one hour of exposure, the temperature exceeded 925°C (1697°F).

The results in Table 6 indicate that there is a correlation between high HRR and high temperatures. Ingason has shown that the highest temperatures (>1300°C or 2372°F) are obtained with HRRs larger than 20 MW (68 MBtu/hr) and low ceiling heights (approximately 4 m to 5 m) in combination with intermediate ventilation rates. For high HRR, the flames reach the ceiling and the combustion zone where the highest temperatures are usually found. It is located close to the ceiling, even when the longitudinal ventilation deflects the flames. When the longitudinal ventilation rate increases further, the cooling effects predominate and the temperature drops again. The geometrical shape and size of the fire, the tunnel cross section (especially the height), and the ventilation rate are thought to be the principal parameters that determine the temperature level at the ceiling. (See web-only Appendix E for additional information.)

General Observations on Large-scale Tests Based on Reported Results

The recent research programs are based on complete measurement systems. They use numerous instrumentations and are organized into networks quite similar to the mesh used in CFD models.

One of the characteristics of these experiments is that no access is possible in the fire area. No visual observation is then possible, except when a video camera is installed in that zone. In some cases, operators could be present in the sections located upstream from the fire. This situation cannot provide an overview of the experiment.

In these conditions, a large amount of recorded data would be helpful to build interpretations concerning the phenomena developed during the fire. The type of measurement instrumentation and its location on three-dimensional (3D) mesh appears fundamental for the analysis of tests results.

The goal of most of the experiments was not to research the physical relations of the phenomena, but to check specific equipment or materials being sponsored by the vendors. It is difficult to obtain general laws from the full-scale experiments; however, general observations under specific conditions can be made. This is the result of the relatively low number of experiments performed in each program. For example, the Japanese tests were partly planned to provide qualitative information about the escape routes in different air velocity control conditions. This target does not appear to be compatible with the use of the results in scientific models.

Because of the uncertainties on the measurement results, the interpretations generally concluded that the calculated HRR is linked to the method used for its evaluation.

The full-scale experiments generally provide interesting qualitative observations. For example, some opacity situations appear clearly as a combination of the HRR, the nature of the burning object (smoke density), and the longitudinal air velocity. The relatively low number of experiments does not lead to general laws or conclusions. (An exception would be the Memorial Tunnel program because of the large number of tests.) These observations might be used as a reference for more specific research using appropriate tools (small-scale or numerical models).

In general, the measurements made during the experiments can be used as a basis for simulations and particularly for CFD. The qualification of a simulation tool must follow several rules:

- Thematic: a reference experiment must deal with fires in tunnels. Cold smoke tests cannot represent fire behavior.

- Reliability: the quality of the results must be correct. Appropriate instrumentation shall be used.
- Representatively: the measurements have to describe as completely as possible the phenomena that have to be characterized by the numerical simulation.
- Adaptability: even if the previous characteristics are satisfied, the reference experiment must be adapted to a comparison with simulation. For example, chaotic behaviors linked to uncontrolled fires such as vehicle fires are not easy to understand and to integrate as boundary conditions.

None of the large-scale tests completely meet those requirements because of the relatively small number of tests with real vehicles.

The number of experiments is limited because of the huge costs involved in such programs (about $40 million USD for the Memorial Tunnel program). These costs lead to limiting the duration of the program and, as a consequence, the number of affordable experiments.

Most of these tests were performed in abandoned tunnels. For a road application, extrapolations are often necessary because of the reduced cross section and its different shape (e.g., horse shoe instead of rectangular or other shape).

Tests in Tunnels Before or Under Operation

There is a requirement and a standard practice in most countries for performing tests before a tunnel is opened. In the United States, the typical requirement is to test all the systems and perform a cold smoke test for witnessing the smoke movement. Typically, there are no requirements for hot smoke tests or tests of burning vehicles before commissioning in new U.S. tunnels.

Many European countries perform small-size (3–5 MW or 10–17 MBtu/hr fire) hot smoke tests, burning a pan with fuel, while activating the fire life safety systems and simulating emergency response procedures. Tests in tunnels before they are put into operation are generally done with calibrated fires such as fuel pools or wood cribs. Pool fires can be used to obtain steady states, which are needed to measure the combustion rate to evaluate the HRR. There is a substantial amount of information on heptane pool fires. Diesel oil can be used to avoid explosions or to produce more smoke.

In France, to be more demonstrative, they usually burn cars in new tunnels before commissioning a tunnel system. Although it is more expensive, it provides a better simulation of an actual fire event, because the HRR is very chaotic and unpredictable. The tunnel ventilation system effect is better characterized when the thermal situation is stabilized in the pool fire tests; therefore, the use of cars as fire loads is recommended after the fire pool tests are done.

These tests are generally performed in tunnels before they are put into operation to demonstrate if the smoke extraction system will work correctly if an accidental fire occurs. The recent developments of such tests show that the efficiency of the ventilation is linked both to its quantitative capacity and to the way it is operated. As this second point is never treated by recommendations or regulations, specific developments are necessary to determine optimal reactions adapted to the fire (location, HRR, natural ventilation, and so forth).

The second goal of these tests is to show the operators how to react in case of a fire. The tests may be completed with fire department exercises and intervention evaluations.

PIARC (*21*) suggests performing tests before opening the tunnel to establish instructions for fire situations. The second kind of test, suggested during operation, is used to train operators and fire departments. The tunnel must be closed specifically for these tests. One of the PIARC report recommendations is to conduct such tests regularly.

Because the HRR is limited, it is possible to observe the phenomena in different zones of the tunnel, even near the fire. These observations may be correlated with the measurements (smoke motions compared with temperature fields, backlayering evolution, and stratification downstream of the fire, and so forth).

Many tests can be performed in a rather short time. It is estimated that about 20 fires can be studied in one week, considering safety precautions.

Instrumentation is limited, but the evolution of these tests tends to increase the number of sensors. Also, the total amount will be limited because this kind of experiment is distinct from research programs; in particular, it will be difficult to characterize the phenomena occurring at large distances from the fire zone.

The size of the fire must also be limited because these tests must be nondestructive. Actually, it is necessary to limit the product "Heat release rate × Duration." Tests involving 20 MW (68 MBtu/hr) sources were performed, but this value is considered an exception. Generally, the test fires do not exceed 5 MW (17 MBtu/hr). During passenger cars tests, peaks of 7 to 8 MW (24 to 27 MBtu/hr) were observed, but they did not last long.

The Puymorens and Chamoise Tunnel tests have been based on heptane pool fires (*21*). Many different steady states have been characterized and these results have been used to determine ventilation requirements. They have also been analyzed from a scientific point of view to determine the general laws governing smoke motion and other thermodynamic behaviors. For example, during the Chamoise Tunnel tests, it was possible to measure the backlayering distance in each case (Figures 9 and 10). The complete analysis of the various parameters shows that the backlayering distance may be

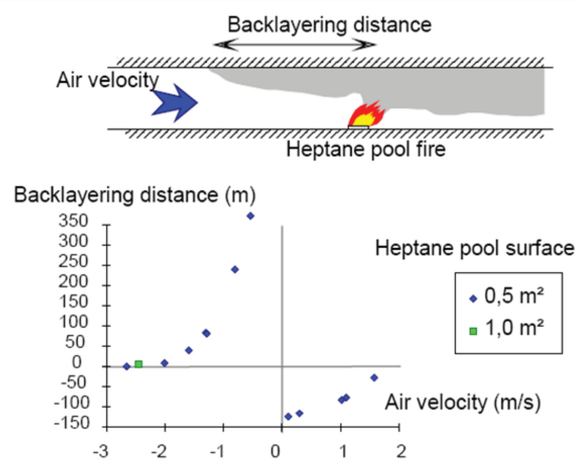

FIGURE 9 Backlayering distance vs. longitudinal air velocity for two heptane pool surfaces [tunnel slope = 0.5 %—Chamoise fire tests (*21*)].

written as a function of the Richardson number (*Ri*) and depends on the tunnel characteristics. The Richardson number considers the density of the gases in the plume impact zone under the ceiling.

SMALL-SCALE TESTING (PHYSICAL MODELING)

Small-scale experiments can be designed to represent a fire in a planned tunnel (see Figure 11). This method is based on similarity laws, which are actually the link between a full-scale situation and the modeled one (*21*).

The objective of such experiments is to represent the phenomena that develop during a fire within a tunnel. Compared with full-scale tests, this method allows some savings of time and money and the ability to analyze the phenomena in detail. Such tests are not affected by natural factors such as winds, elevations, and solar radiation, and can be repeated as many times as necessary. One of its goals is also to be demonstrative, because it is possible to visualize smoke. However, there are only a few examples of reduced-scale model applications for tunnel design that can be mentioned (*30*).

FIGURE 10 Plabutch Tunnel Fire Test sponsored by Graz University of Technology.

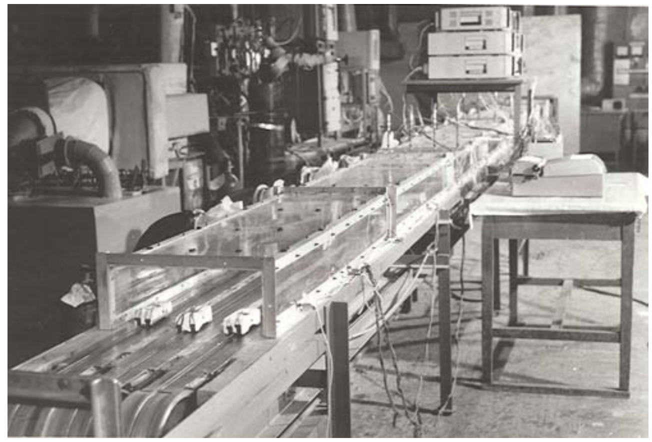

FIGURE 11 Small-scale experiments (physical modeling) (*29*).

One example is a study on smoke stratification stability on a one-third scale model. The Froude scaling enables modeling of thermal effects and smoke backlayering. The fire is modeled using a heptane pool fire and can be characterized by:

- Theoretical total HRR calculated from the mass consumption of heptane.
- Total HRR computed from the oxygen consumption.
- Convective HRR with volumetric flow rate estimated by integration of the velocity profile measured downstream of the fire.

The difference between the two total HRRs is combustion efficiency and radiation fraction.

Researchers can use small-scale models for scientific reasons. If some specific behaviors have to be characterized, the best solution can be to show them using totally controllable methods. Complementary tests may be done with full-scale facilities. The knowledge of the laws obtained with the models is useful in planning full-scale experiments.

Small-scale models have been used to characterize the efficiency of ceiling trap doors for smoke extraction or to determine nondimensional laws governing the existence of backlayering.

The similarity laws are the fundamental link between the model and the corresponding full-scale situation. If this link is not shown to be strong, the study results cannot be considered as representative of the full-scale situation. Actually, in a more general manner, the validity of the experiments has to be considered as relative to the used similarity law. As a consequence, it depends on the small-scale model technique.

The situation observed during a fire inside a tunnel appears as the result of an interaction between two major forces:

1. Force induced by natural or mechanical effects. It is characterized by the air velocity obtained upstream of the fire, U.
2. Buoyancy forces developed in the fire plume, which are induced by the gases' expansion resulting from the high temperature. The fundamental characteristic is given by the density difference between the air and the hot gases, $\Delta\rho$.

To represent the turbulent longitudinal flow, it appears necessary to use the Reynolds number *Re:*

$$Re = UD_h / v \quad (14)$$

where:

D_h represents the hydraulic diameter, and
v represents the fluid cinematic viscosity.

The effect of buoyancy forces are partially represented by the Froude number, *Fr:*

$$Fr = U^2 / gD_h \quad (15)$$

where g represents the gravity acceleration.

The Froude number modified with the density differences represents the gravity effects on fluid motions, resulting in the Richardson number:

$$Ri = \left(gD_h / U^2\right)\left(\Delta\rho / \rho\right) \quad (16)$$

Other parameters may be used to study phenomena on reduced-scale models. For example, the Grashof number is a combination of the Reynolds and the Richardson numbers:

$$Gr = \left(gD_h^3 / v^2\right)\left(\Delta\rho / \rho\right) \quad (17)$$

The Reynolds condition is generally limited to checking that the Reynolds numbers in the model are sufficient to ensure the turbulent character of the longitudinal airflow.

The thermal exchanges with the walls are difficult to model exactly as they would appear in an actual tunnel.

The relation between the backlayering distance, the local slope, the heat release, and the thermal exchanges with the walls has been demonstrated using small-scale models. Density change represents temperature and vertical velocity as the function of burned gases.

The fire source can be modeled by a flux mixing a light gas (generally helium) and air or nitrogen. These models cannot represent thermal exchanges with the walls. The isothermal source does not take into account the physics of fires. In realistic situations, the combustion temperature is related to the vertical velocity. In the experiments, these two parameters are not dependent. Such experiments have been used to characterize the limits of the existence of backlayering. These experiments have been associated with a CFD technique. The good correlation obtained shows that the control of the boundary conditions in the experiments was correct and that they could be correctly described in order to perform numerical simulations. It is to be noted that the characterization of these boundary conditions for full-scale tests remains a problem.

Using a small-scale model to design a tunnel ventilation system may be limited for two primary reasons:

- Technical conclusions are relative to the similarity law(s) used. A fire is a complex phenomenon and its representation cannot be limited to one or two global relations.
- HRR representation remains an unsolved problem.

It is not correct to conclude that the lack of total similarity leads to unrealistic results. For example, the conclusions drawn from small-scale experiments performed in the Channel Tunnel on shuttles have been confirmed later through full-scale tests.

The representation of realistic situations with reduced-scale models depends on the number of similarity laws taken into account. As only one parameter is simulated (Froude or Richardson number), the global validity of this kind of study is not accurate. The application of this technique to full-scale situations is not immediate. As an example, the conclusions drawn from the study concerned with trap doors or single-point extraction openings, recently done in France, have been applied to other projects because they provide valuable answers concerning the relative capacities of the various systems; however, absolute results were not used.

The second case is the use of small-scale models for research. The conclusions of such studies are generally limited to the model studied. The transposition of the established laws to full-scale situations needs reference experiments. Therefore, the interest of these models is to show that general laws can be drawn from the study of specific situations, which also give analytic form for these laws (e.g., existence of backlayering versus source characteristics and longitudinal air velocity.)

In general, the validity of a study based on the use of models is directly linked to the interpretation of the similarity law.

LARGE-SCALE EXPERIMENTAL FACILITIES

Such tests can be considered to be somewhere in between a full-scale road tunnel test and small-scale laboratory tests. An example of such a facility is a laboratory tunnel of Carleton University, located in Almonte, Ontario, Canada, which is used for performing large-scale experiments. The tunnel is 37.5 m (123 ft) long and the cross section is 10 m (32.8 ft) wide and 5.5 m (18 ft) high. The tunnel has a shutter opening [3.8 m wide (12.5 ft) and 4.0 m (13.1 ft) high] and two louvered openings [1.2 m wide (3.9 ft) and 4.5 m (14.8 ft) high] at the east end. Figure 12 is a schematic diagram of the tunnel facility.

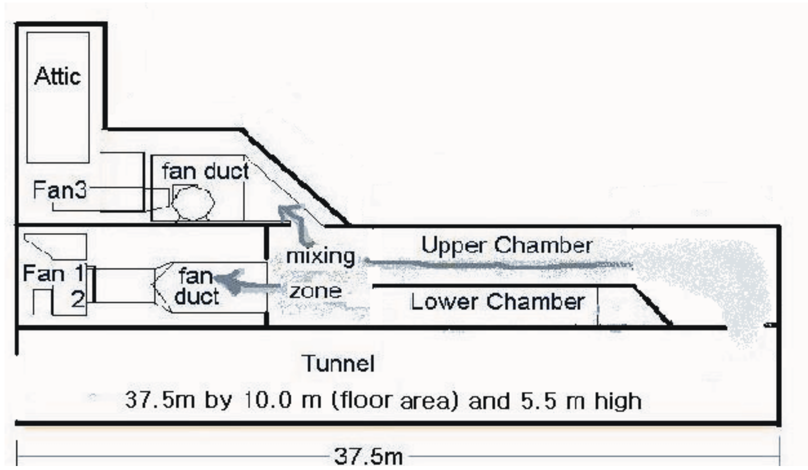

FIGURE 12 Schematic diagram of the laboratory tunnel facility of Carleton University (*31*).

This facility was recently used to study the impact of tunnel suppression on tunnel ventilation systems. The absolute cooling effect and radiation attenuation were examined by activating the sprinkler system over a propane fire, which generated a constant HRR. The test examined the effectiveness of the longitudinal ventilation system with the sprinkler system active. When the sprinkler system was turned on, some smoke escaped from the tunnel openings; however, overall, the ventilation system was able to control the smoke. The sprinkler system cooled smoke, caused steam formation, and lowered visibility. With the sprinkler system active, ceiling temperatures upstream of the fire and in the spray section dropped dramatically. It was found that the sprinkler system and ventilation system effectively cooled down smoke and reduced the heat flux. The measured heat fluxes showed that the absorption of thermal radiation and transmission of the radiation can be affected by the sprinkler system and air flow in the tunnel. The longitudinal air flow in the tunnel was affected by the discharge of water sprays because the air flow velocity was as low as 1 to 2 m/s (197 to 394 fpm). However, the ventilation system was able to control smoke in the tunnel. As the sprinkler system reduced the smoke temperature, it could be expected that the driving force to propagate the smoke decreased, thus enabling the longitudinal ventilation system to prevent backlayering of smoke.

GAPS IN FIRE TESTING, MODELING LIMITATIONS, AND COMPUTATIONAL FLUID DYNAMICS VERIFICATIONS

The Memorial Tunnel Fire Test program produced a substantial amount of valid information and test results for further studies. However, the program used fuel pans to simulate fire. There have been no full-scale fire test programs with real cars, buses, and trucks in the United States. The National Fire Protection Association (NFPA) uses information on HRR from the tests performed in Europe and Japan, but recognizes that the open trucks tested in those countries are not used in the United States. It also recognizes that test conditions did not represent typical road tunnel geometry, but used smaller tunnel sections. There is a need for full-scale fire tests using real vehicles to verify FHRRs with fewer corrections to local conditions.

A set of full-scale tests in Europe provided valid information on HRRs from cars and HGVs. Limited information was provided on bus fires and no information on gasoline tanker fires.

The UPTUN fire tests did not provide much information on smoke and other gases dissipating from the fire during the tests. Smoke dissipation data were obtained during tests in Japan and information appeared in the PIARC and NFPA 502 documents; however, those tests were outdated and the smoke production rate was removed from the documents. Design engineers are advised to select a material, such as polystyrene, mineral oil, polyurethane foam, or wood cribs to calculate smoke production rate. It was noted that smoke was the leading cause of death. A lack of such information could be considered as a significant gap in fire testing. Some observations made during recent fire events noted that smoke is produced faster than the fire grows. This may be associated with the materials burning first. Modelers typically use a linear relation between the HRR and smoke production rate, which may lead to underestimates of smoke development during the evacuation phase.

Numerical modeling has become a tool of choice for design engineers modeling tunnel fires. Designers need to select appropriate physical models and boundary conditions to model fire events. One of the unknowns is the turbulent model. It has been demonstrated in the past that different turbulence models and different coefficients in those models can lead to different (sometimes opposite) results. Design engineers often uncritically use turbulence models proposed by the CFD packages and some default coefficients with little if any understanding of the accuracy of their selection. However, there were no road tunnel fire tests that required instrumentation that would allow for the measure of turbulence scale. Therefore, the user inputs the recommended turbulence models and model coefficients, which can lead to incorrect design or speculation on the modeling results.

The best way to learn is with actual tests. Commissioning for fire life safety systems is done in other countries by burning vehicles in the tunnel before the tunnel opens to the public. Cold smoke tests or small fuel pan fire tests do not replace a real vehicle fire. Such tests will allow the testing of the design and all the systems, as well as the training of operators, first responders, and design engineers.

Some small-scale fire tests (physical modeling) are an important scientific research tool that needs further development to allow better understanding of the physics involved and to see the final results. Such tests allow for the installation of precise instrumentation and the ability to repeat the tests, while enabling easy changes of the parameters and systems responses, as well as fine tuning the systems before the tunnel is built. It also allows for the checking of CFD models.

SUMMARY

Fire tests are of vital importance to the understanding of the physics of tunnel fires, understanding the impacts of fires, and verifying calculations, assumptions, computer models, and tunnel design. They are also important for tunnel operators and emergency responders to coordinate the efforts and verify in practice the emergency response plans.

Fire tests have been performed and can be classified as:

- Tests before the design to develop design methodology.
- Tests during the design to verify assumptions and computer models.
- Tests during commissioning to verify the design and equipment operation.
- Tests for training purposes.

Important conclusions and recommendations that were determined from full tunnel fire tests included:

- Ofenegg Tunnel Test results that raised doubts in sprinkler systems for road tunnels. Important conclusions on the danger of delayed sprinkler activation or early deactivation of the sprinkler system were observed.
- Zwenberg Tunnel tests strongly supported the benefits of a fully transverse system running in a full extraction mode during a fire once the fire is quickly detected and ventilation mode correctly activated.
- PWRI experiments concluded that the stratification of smoke was partially destroyed by longitudinal ventilation at 1 m/s (197 fpm) and totally destroyed by longitudinal ventilation at 2 m/s (394 fpm). They concluded that the sprinklers had an adverse effect on the tunnel environment by causing a reduction in smoke density near the ceiling and an increase in smoke density in the lower part of the tunnel.
- Repparfjord Tunnel fire tests registered that the temperatures during most of the vehicle fires reached maximum values of 800°C to 900°C (1472°F to 1652°F). The temperatures during the HGV test reached 1300°C (2372°F).
- Benelux Tunnel tests concluded that sprinklers reduced temperatures to safe levels upstream and downstream of the fire and also reduced the probability of fire spreading between vehicles.
- The Memorial Tunnel Fire Ventilation Test Program performed 91 tests with diesel oil pool fires in an abandoned 850-m-long road tunnel located in West Virginia, with fire sizes of 10, 20, 50, and 100 MW (34, 68, 172, and 341 MBtu/hr). Diesel oil pool fire tests do not allow making conclusions on among other issues the expected real tunnel fire size, growth rate, smoke generation rate, and real smoke stratification. Tests were performed with various ventilation systems including:
  - Full-transverse ventilation
  - Partial transverse
  - Single-point extraction
  - Oversized exhaust
  - Natural ventilation
  - Longitudinal ventilation with jet fans.

  Tests concluded that a 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 in a 3.2% grade tunnel, which allowed for its application in the United States.
- The Runehamar Tunnel fire tests alarmed the industry with a 200 MW (682 MBtu/hr) HGV fire size and its fast growth.
- UPTUN Project tests indicated that there is a correlation between high HRR and high temperatures. The geometrical shape and size of the fire, the tunnel cross section (especially the height), and the ventilation rate are thought to be the principal parameters that determine the temperature level at the ceiling.

Most of these tests were performed in abandoned tunnels. Each test was done differently and had its own purpose(s), often driven by the sponsors and vendors. The tests had different methodologies and were performed in tunnels of different configurations. For a road application, extrapolations are often necessary because of the reduced cross section and its different shape.

The full-scale experiments generally provided interesting qualitative observations. The relatively low number of experiments does not lead to the creation of general laws. (An exception would be the Memorial Tunnel program, because of the large number of tests conducted.) It appears that the ideal full-scale test is one that can be done in a typical size and shape road tunnel using actual cars and trucks for burning, can perform a large number of experiments, is well-prepared and equipped with the precise instrumentation suitable for the test conditions, and allows for the generalization of the test results on both macro- and micro-levels.

The international practice of commissioning tunnel fire life safety equipment and fire fighting procedures using hot

TABLE 7
FIRE TESTS FOR RESEARCHES, DESIGNERS AND OPERATORS

Means	Use for Research	Use for Design	Use for Operation
Full-scale Fire Test Programs	Advantages: - Direct interpretation - Complete results Disadvantages: - Cost - Limited number of tests Conclusions: - Well suited	Advantages: - Direct interpretation - Possibility of using real road vehicles Disadvantages: - Cost - Limited number of tests - Geometry of the test facility Conclusions: - This solution depends on the importance and specific problems of the project (e.g., Memorial Tunnel)	Advantages: - Direct interpretation Disadvantages: - Cost - Limited number of tests Conclusions: - Unrealistic if not associated with other objectives
Tunnel Fire Tests Before or Under Operation (aimed at optimizing ventilation responses in fire event)	Advantages: - Partial results with full-scale facilities - Numerous different situations Disadvantages: - Lack of information due to the limited number of sensors Conclusions: - Useful but partial results	Advantages: - Accumulation of experience useful to choose a system - Test performed with real ventilation systems Disadvantages: - Limited number of tests Conclusions: - Useful	Advantages: - Shows operators how the ventilation reacts - Fire departments are very interested in expected situation Disadvantages: - No operation possible during the tests Conclusions: - Well suited
Tunnel Fire Tests Before or Under Operation (aimed at operators and fire department training)	Advantages: - Visual observations possible Disadvantages: - Lack of information due to the absence of sensors Conclusions: - Not suited	Advantages: - Test performed with real ventilation systems Disadvantages: - Limited analysis due to the lack of measurements Conclusions: - Not well suited	Advantages: - Representative situation Disadvantages: - No operation possible during the tests Conclusions: - Well suited
Reduced-scale Models	Advantages: - Many tests possible - Possibility of studying global laws governing specific situations Disadvantages: - Needs full-scale reference tests for transposition to real situations Conclusions: - Useful method for research	Advantages: - Cost lower than full-scale tests. Disadvantages: - Linked to the limitations induced by the similarity laws Conclusions: - Very difficult to conclude that the results are representative of full-scale situations	Advantages: - Cost Disadvantages: - Linked to the limitations induced by the similarity laws - No respect of time basis Conclusions: - Possibly unrealistic but demonstrative

smoke tests and burning actual vehicles in the tunnels needs to be evaluated for future national standards considerations.

Small-scale experiments can be designed to represent a fire in a planned tunnel. This method is based on similarity laws, which are actually the link between the full-scale situation and the modeled one. Compared with full-scale tests, this method allows for some savings of time and money and for analyzing the phenomena in detail. Such tests are not affected by natural factors such as winds, elevations, and solar radiation, and can be repeated as many times as necessary.

Using a small-scale model to design a tunnel ventilation system may be not be practical for two main reasons:

- Technical conclusions are relative to the similarity law(s) used. A fire is a complex phenomenon and its representation cannot be limited to one or two global relations.
- HRR representation remains an unsolved problem.

Large-scale tests can be considered to be somewhere between a full-scale road tunnel test and small-scale laboratory tests. Table 7 summarizes benefits for research, design and operation of tests and models, and their advantages and disadvantages.

There have been no full-scale fire test programs with real cars, buses, and trucks in the United States. There is a need for full-scale fire tests using real vehicles in real road tunnels to verify FHRRs with fewer corrections to local conditions.

CHAPTER SEVEN

ANALYTICAL FIRE MODELING—LITERATURE REVIEW

Information from numerous test reports has shown that road tunnel fire tests are expensive, require precise measurements, and are difficult to reproduce. Numerical modeling can be repeated and allows for easy change of control parameters. Numerical modeling helps researchers to understand the physical processes and influences from design parameters. Validation of numerical models against the fire tests helps to expand the models to new projects. However, validation of numerical fire models is complicated and in most cases not successful, although some parts of the numerical model can be verified against tests and field measurements, considering that appropriate measurements have been made during the fire tests.

Theoretical models, especially computer-based models, can be very valuable in assisting tunnel fire safety decision making. However, such models are also capable of being misleading. Nowadays, computer-based simulation models are widely used to calculate propagation of smoke and hot gases to assess the means to improve tunnel safety. They enable the simulation of the interaction of various fire parameters.

CFD software can model emergency fire operating conditions in tunnels and predict the resulting contaminant concentration levels. In areas of geometrical complexity, CFD is the appropriate tool for predicting 3D patterns of airflow, temperature, and other flow variables, including concentration of species, which may vary with time and space. CFD was developed as a scientific tool for the investigation of aerodynamic and thermodynamic processes. Nowadays, CFD software is considered as the design tool of choice for obtaining an optimum design, because experimental methods are costly, complex, and yield limited information. However, it requires in-depth knowledge of physical processes and numerical models and, preferably, testing experience from the numerical modeler.

Many commercial CFD packages have been developed in recent years. A Fire Dynamics Simulator (FDS) is a CFD model of buoyancy-driven fluid flow from a fire. A separate code called Smokeview (OpenGL graphics program) is used to visualize data output from an FDS. These applications can also be configured to model pollutant levels outside the portals and around the exhaust stacks of tunnels. Both of these public domain programs are under active development and can be obtained from the National Institute of Standards and Technology (NIST). FDS uses the Large Eddy Simulation to solve the large scales of motion and model the small scales that are assumed to be universal. The Large Eddy Simulation results in a transient solution to the actual Navier–Stockes equations valid for a low-speed (low Mach number) buoyancy-driven flow.

A specific CFD model called SOLVENT was developed as part of the Memorial Tunnel Fire Ventilation Test Program for simulating road tunnel fluid flow (ventilation), heat transfer, and smoke transport. SOLVENT can be applied to all ventilation systems used in road tunnels, including those based on natural airflow. SOLVENT has not been used for modeling fixed fire suppression systems and has some other limitations.

Other CFD programs, both commercially available and in the public domain, have been used to model fire scenarios in road tunnels, the list of which is too numerous to include here. The most common and powerful for tunnel applications are ANSYS (Fluent CFD) and CFX verified against testing results.

Initially, the strengths and weaknesses of each program are investigated. Validation of the results against experimental data or another equivalent program is encouraged. Some programs have limitations and are unable to model the required processes, including water-based fire protection, moving traffic (sliding mesh), wall roughness, and so forth. Validation is challenging for tunnel fire modeling because the experimental data are far from absolute, given the complexity of the physical process. Good experimental data are required.

It becomes difficult to check the CFD model and results. In many cases it is up to the artistic, inventive ability of the engineer who created the model. The knowledge and experience of the user becomes crucial. Users may employ different inputs in applying the same models or use different deterministic models to the same case, both of which produce different results. Some studies showed significant differences when the same user applied two different CFD-based models to the same case. The user must be knowledgeable about tunnel fire science, as well as the model's limitations and applicable conditions.

Assessment of models and their results are important and must be conducted by experienced people. It is important to establish a procedure for producing comprehensive, iterative assessment of fire models.

ANALYTICAL (NUMERICAL) FIRE MODELING TECHNIQUE

The CFD simulations of tunnel fires driven by buoyancy forces with significant energy release require a solution of the Navier–Stokes equations with appropriate boundary conditions. The physics of fire modeling is complicated by many uncertainties. A number of assumptions need to be made for numerical modeling. The number of unknown variables and the calculation duration vary according to the hypotheses and assumptions made.

There are at least eight equations to solve in 3D simulations, the unknown variables being ρ, p, T, u_x, u_y, u_z, k, and ε, and seven equations to solve in two-dimensional (2D) simulations.

Additional equations may be required to take into account the radiative heat transfer, the combustion process, or the heat transfer by conduction inside the walls. Different ways to model fire have been discussed. Airflow in tunnels is usually turbulent and the user has to make an assumption on the type of turbulence modeling to apply. One of the most common turbulent models is the k-ε model and its variations. The user is required to select turbulent length scale along with k and ε coefficients. There is insufficient information from a full-scale test to provide recommendations on the coefficients to use. With this lack of information, the users apply the default numbers or follow some recommendations that may not be applicable to the road tunnel fire test modeling. The better choice is to calculate the k and ε coefficients of the model based on length scale.

In recent years the development of computers (i.e., speed and memory) has allowed for the development of larger and more complicated numerical models. However, considering the length of road tunnels, a model may require millions of cells. Even with today's computer power, the transient simulations of this size of a model may take months of computer time. Usually the user has to examine the grid by performing sensitivity analysis and find the grid scale that will allow for reasonably accurate simulation results (*32, 33*). The better (fine) grid quality is usually in the fire influence zone, whereas a coarser grid is created in other parts of the tunnel.

A road tunnel fire is a combustion process with many unknowns, such as the substance that is burning, the method of the burning, and when it is burning. Some conservative assumptions can be made based on previous experience and full-scale fire tests. Those assumptions may include fire growth and decay rates, ignition location, and fire size. However, how the vehicle burns may be one of the most complicated questions for the numerical modeler, especially if modeling a fire as a chemical reaction, providing soot particles and combustion products at high temperatures. One approach is to represent a vehicle as a blocked volume, consider vehicle windows as inlet boundaries, and have hot combustion gases emerge as the flame temperature.

For combustion process modeling, the Eddy-Break-Up model is generally used. This method may be helpful if the information required from the simulation concerns the fire zone. The limitation concerns the fire load. It is not always possible to provide equivalence in terms of fuel consumption.

In December 2005, NIST performed CFD modeling of the 1982 Caldecott Tunnel Fire (*34*). They used the FDS code and a combustion model. They concluded that fire consumed roughly 70% of the available oxygen, with an HRR of about 400 MW (1,365 MBtu/hr). However, the authors accepted that this was probably an overestimate because the model uses a simple "mixed is burnt" combustion model in combination with an empirical local extinction algorithm. The actual combustion processes are far more complicated and potentially much less efficient in the tunnel environment. The model overly predicted the combustion efficiency of the fire, in which case most of the fuel was consumed somewhere in the tunnel or never consumed at all. Another possibility was that the observed flames at the east portal were a result of unsteady evaporation of the gasoline. It was assumed that the gasoline evaporated at a constant rate for 40 min (about 10 kg/s or 22 lb/s). However, had there been periods of greater evaporation this would explain the discrepancy between the observations and the simulation. The maximum predicted gas temperature near the ceiling was just below 1100°C (2012°F) with ablation and 1150°C (2102°F) without. This high temperature region was located roughly 40 to 120 m (131 to 394 ft) east of the overturned truck, near the ceiling and along the tunnel centerline. However, the tunnel inspection report suggested that the maximum gas temperature could not have exceeded the melting temperature of copper [1065°C (1949°F)], because copper wiring in the upper wall light fixtures was not melted. The peak wall surface temperatures were approximately 950°C (1742°F).

A more simplified approach is to consider fire as a volume source of energy at a given changing FHRR and a source of smoke and soot as a function of HRR. The last approach does not require combustion and chemical reaction modeling, but does require knowledge of the heat, smoke, and soot release rates.

- Fixed HRR in a volume: In this model, the fire source is represented by an HRR fixed inside a given volume. This value is not influenced by ventilation. This method leads to a more accurate energy distribution inside the tunnel volume, and experience has shown that it can lead to quite realistic temperatures except very near a fire.
- Fixed heat flux through a horizontal surface: This technique imposes a heat flux or a mass flow rate at a fixed temperature to get the design HRR. The latter method leads to the mass flow rate, which is not always in agreement with the combustion's production of burned gases (it must then be combined with a sink of mass). The volume energy distribution is not as good as in the previous case, and the results are not as reliable.

- Fixed temperature in a volume: The advantage of this method is its ability to control the maximum temperature reached inside the fire. A disadvantage of this method is that the HRR will strongly depend on ventilation conditions.

The fixed HRR in a volume method is generally preferred because it is less expensive (central processing unit time) than modeling the combustion process and presents fewer disadvantages than the other methods. The design HRRs and fire curves can be directly used with this method.

It is always suggested that sensitivity studies be performed before final design simulations. This may take more time and effort than the design, but leads to a better understanding of the results.

There are many other boundary conditions that may affect the end results.

- Initial air movement—Air in the tunnel is never still. There is always some airflow caused either by the piston effect of traffic, by normal tunnel ventilation, or by winds and other natural factors. For example, in uni-directional tunnels, the assumption is made that in a fire emergency traffic will be trapped behind the fire, whereas traffic downstream of the fire will leave the tunnel. The departing traffic will cause a residual piston effect, driving smoke and airflow in the direction of travel. Adverse winds may also have a significant impact on the airflow. Residual air movement, caused by approaching the fire location traffic, may also drive the airflow.
- Trapped traffic behind the fire incidence—Trapped traffic creates a significant obstruction to the airflow. This results in substantial resistance to the airflow and obstructions to the air jets developed by the tunnel ventilation system. The last phenomena could be modeled by CFD; however, it would require complicated geometric modeling and many additional computational grid cells.
- Wall boundary conditions—It is usually considered that approximately 30% of the total heat is transferred to the tunnel walls by radiation and 70% by convective heat. There are radiation models available in commercial CFD products; however, radiation models are complicated and require the use of absorption coefficients and other empirical information. Often users consider convection portions only. Temperatures inside the fire may reach 1300°C (2372°F). The heat transport is locally more radiative than convective. Calculations performed without radiative models have led to the prediction of higher temperatures, even a 100 m from the fire zone. Several techniques can be used to take radiation into account.
- Radiative heat transfer model coupled with the conservation equation of energy—This technique solves an additional equation. The greatest difficulty comes from inadequate knowledge of the radiative properties of smoke, which explains the need for additional research on this topic.
- Control of heat fluxes at the walls without modeling the radiative heat transfer—This solution entails combining the radiative and convective heat transfer coefficient to form a local empirical transfer coefficient. No additional equation is required. In France, this method has been applied to simulate the heptane fire test H32, which is carried out during the EUREKA 499 experiments. Results obtained with this method are claimed to be within reason.
- Reduction of the HRR at the fire source—This considers reducing the actual heat release source injected in the model by deducing the radiative part. This technique has been shown in several publications and the percentage of energy lost by radiation at the fire source is estimated to be in the range of 20% to 50% of the total heat energy released by combustion. The major problem with this method is caused by not taking into account the loss in radiative energy from the hot gases to the walls farther from the fire.

Smooth wall surfaces are generally the default CFD conditions. However, the user may generally define rough surfaces by modifying the layer parameters to represent the zone very near the walls. The use of rough surfaces depends on the objectives of the simulations; if they concern the analysis of the force's balance or the propagation speed of the smoke front, the assumption made on surfaces will influence the results.

Heat transfer boundary conditions may also affect the end results.

- Fixed temperature or fixed heat fluxes—In this case, the temperatures at the walls or the heat fluxes through walls are fixed to constant values.
- Combination of fixed temperature with heat fluxes—This technique may be used to roughly model the heat conduction process in the rock (soil).
- Heat conduction inside the rock (soil)—This method appears as the best physical interpretation of the problem. The heat transfer to the walls may have noticeable effects, especially in the case of extended fires. However, it leads to larger meshes and longer calculations.

Boundary conditions at the portals may seriously influence the final results.

- Fixed pressures at both portals—This directly represents the atmospheric effects. The critical size of the outside zone to be modeled is between 3 and 5 hydraulic diameters. However, acceptable results can be obtained without an outside domain, provided that some precautions or even corrections are used.
- Specifying fluid properties fixed at one end and fixed pressure at the other end—This may be justified for the analysis of the conditions inside the tunnel with known

ventilation effects. The upstream condition appears to be quite limited, because it forces the flow in one direction, especially if the velocity's components are imposed. For modeling, it may be more reasonable to specify different pressure boundary conditions at the portals, such as wind effects.

Simplifying the model can also have an effect on the results.

Another challenge is in setting the time step for transient modeling. Sensitivity analyses are suggested to select the appropriate time step. The use of simplified models may be applicable for long tunnels for which the boundary conditions are difficult to describe. A simplified model, such as a one-dimensional (1D) model, can be used to estimate globally the flow in the complete tunnel and derive the boundary conditions to impose at both ends of the mesh. Simplified 1D models can evaluate the critical fire locations, depending on the tunnel geometry and ventilation scheme.

As a first approach a simplified model, such as a 1D model, is used to estimate globally the flow in the complete tunnel and derive the boundary conditions to impose at both ends of the mesh for 2D and 3D models. Simplified 1D models are used to evaluate the critical fire locations depending on the tunnel geometry and ventilation scheme, evaluate ventilation requirements, and provide ample sensitivity information.

Although 3D simulations require long calculation times, 2D simulations may appear as attractive alternatives. This simplification of the problem by utilizing a flow between two planes requires some precautions, such as:

- To take into account the reduction of the friction forces, and
- To perform modeling using similarities based on the Reynolds and Froude numbers and energy dimensionless parameters.

The energy dimensionless parameters represent the energy released by the fire or the quantity of fuel injected per square meter (square foot) of tunnel cross-sectional area. Therefore,

$Q_{\text{fire}}/S_{\text{tunnel}}$ is the name in 2D or 3D (*21*),

where:

Q_{fire} is the heat release rate, and
S_{tunnel} is the tunnel cross-sectional area.

These constraints influence the geometrical and gravitational terms. A validation assessment has been performed on the basis of Ofenegg Tunnel experiments.

Some important limitations must be mentioned. For example, this technique does not correctly describe the stratification in the instance when the longitudinal velocity is lower than the critical value. Consequently, 2D simulations require specific precautions and can be used in specific situations only.

FINDINGS ON NUMERICAL MODELING BASED ON LITERATURE REVIEW

The main advantage of the CFD models is to allow the study of cases for which no experimental data are available. After a preliminary validation has been made from full-scale tests, simulations are used to study many other situations. This technique provides a general description of the various phenomena. This is the only method that offers such possibilities, even if the results must be considered as orders of magnitude.

The major restriction is the time needed for the calculation and the complexity of the model. Lengthy preliminary validations and skillful users are necessary; otherwise the obtained results may be misleading.

The CFD models are therefore adapted principally to certain specific uses:

- To set up general design rules by simulating typical cases.
- To investigate new or especially complex situations.
- To obtain a thorough understanding of actual fires and to analyze them.

Moreover, there are many advantages that can be drawn from the use of CFD models in conjunction with other study methods. For instance, full-size testing will benefit from some preliminary computational simulations (if necessary, very approximate) to assess the expected phenomena and their orders of magnitude. Also, a test program on scale models could advantageously be prepared by calculations aimed at evaluating the quality of similarities and orders of magnitude. The reduced-scale model will then allow for studies by varying the useful parameters. Last, new calculations can be made to calibrate the computational code in a first step, and in a second step to understand, even extrapolate the model measurements.

To simulate fires in long tunnels or complex underground networks it may be useful to couple a 3D simulation with simplified ones, such as 2D or 1D models, to determine boundary conditions. This technique appears as a potential development of the numerical simulation.

The CFD models include several physical models that have been validated against fundamental experiences, but where few global validations have been made on full-scale fire tests. Therefore, the databases drawn from the EUREKA 499 and the Memorial Tunnel experiments are very useful for validating CFD models (*35*).

A plan to set up a CFD model that has been calibrated and fitted with the numerous parameters that can easily be used by an unskilled user is probably not realistic. A preliminary validation work must compare qualitatively and quantitatively

TABLE 8
OBJECTIVES OF ANALYTICAL FIRE MODELING FOR TUNNEL FIRE SAFETY

Means	Use for Research	Use for Design	Use for Operation
Numerical Models (CFD)	Advantages: - Possibility to study many different situations - Information on flow structures unattainable with other methods Disadvantages: - The conclusions must be correlated to existing experimental references Conclusions: - Useful method for research	Advantages: - Possibility to get an optimization by the use of different assumptions Disadvantages: - The model requires qualification Conclusions: - Useful method for projects, if validated	Advantages: - Possibility to describe the physical conditions in several locations of the tunnel Disadvantages: - Theoretical results lead to theoretical conclusions Conclusions: - The adaptation depends on the use of the model

Source: PIARC (*21*).

calculated results and measurements to define rules for running fire simulations. However, it may be able to fit all the parameters without physical reasons because such calibration could not be transposed to other configurations.

The international community has made large efforts and investments in research programs on fire safety in tunnels during the last decade. The number of international congresses on this subject, the development of fire model and large fire test programs carried out in recent years in Europe and in the United States (Memorial Tunnel) confirm this tendency.

The CFD codes are already largely used to study fire situations in tunnels; however, additional research and validation works are required to ensure the validity of their results.

Some research is required to improve existing models, such as turbulence or combustion models. This research is generally done by universities and laboratories, the activity of which deals with fundamental fluid dynamics phenomena and development of CFD codes.

With the development of the sprinkler system application for road tunnels came the need to model its performance. Much research has been published on CFD modeling of sprinkler systems and water mist systems (*36–40*); however, there is a need to validate the sprinkler models against full-scale tunnel fire tests. Additional research is needed for numerical modeling of sprinkler system impacts on flame and fire size.

The next step is to undertake new small- and large-scale experiments with the primary objective of validating and calibrating physical models. It may include understanding of flow generated by fire as well as measurements of some physical smoke properties, which are critical for models (i.e., radiative smoke properties, generation of soot).

SUMMARY

Theoretical models, especially computer-based models, can be valuable in assisting tunnel fire safety decision making. However, such models can also be misleading.

Nowadays, CFD software is considered as the design tool of choice for obtaining an optimum design, because experimental methods are costly, complex, and yield limited information. However, it requires in-depth knowledge of physical processes and numerical models and, preferably, testing experience from the numerical modeler.

The CFD simulations of tunnel fires driven by buoyancy forces with significant energy release require a solution of the Navier–Stokes equations with appropriate boundary conditions.

Table 8 provides a summary of the objectives of analytical fire modeling for tunnel fire safety based on the literature review.

Many commercial CFD packages have been developed in recent years. Initially, the strengths, weaknesses, and limitations of each program are investigated. Validation of the results against experimental data or another equivalent program is necessary in order to have accurate results. Most of the commercially available CFD codes used in this synthesis report have been validated against some tests; however, at times users try to stretch the software application to areas where the applications have not been validated. For example, it is difficult to find a CFD program that has been validated for sprinkler system application in full-scale tunnel tests. The same applies to turbulent models; radiation models applied for road tunnels. There is a need for additional tests and validations of the CFD models for road tunnels.

CHAPTER EIGHT

SURVEY RESULTS

The survey was sent to the states and agencies in the United States that manage tunnels and to international tunnel agencies. There are a number of U.S. states where there are no road tunnels; the survey was not sent to those states. Nine U.S. agencies reported on 32 tunnels, which represent approximately 60% of the U.S. agencies that were addressed by the survey. In addition, the survey was distributed to international tunnel agencies to document the best international practice. A total of 15 agencies worldwide reported on 319 tunnels.

This is a summary of the data gathered from the 15 agencies that responded to the NCHRP Design Information on Fires in Road Tunnels (Topic 41-05) on-line questionnaire. Some of the agencies reported on each of their tunnels in separate surveys. Most of the agencies combined multiple tunnels into a singular survey response. The nine U.S. tunnel agencies reported on the 32 tunnels cited in Table 9 and the six international agencies reported on the 287 tunnels cited in Table 10.

Not all agencies responded to every question. The actual number of responses for each answer, obtained from the survey data, can be found in Appendix C. The first part of Appendix C shows national data, the second part international data.

In addition, there may be more choices made then the number of responders for the "please check all that apply" questions. Therefore, the "total" percentages may not add up to 100% for these questions. Open text responses are taken verbatim.

FIRE FREQUENCY IN U.S. TUNNELS

Fourteen of 29 national tunnels (48%) reported that the annual tunnel vehicle fire incidents number 1 to 2 every year for each tunnel, whereas 11 of 29 tunnels (37%) reported no occurrence of fire. The Port Authority of New York & New Jersey was the only agency that reported having from 2 to 5 vehicle fire incidents per year, which can be explained by the volume of traffic in the Holland Tunnel.

Ten of 19 reporting tunnels (52%) reported that the most severe vehicle fire incidents in their tunnels occurred from a heavy goods truck. No tanker fires happened in these tunnels.

Outside the United States, two agencies reported annual vehicle fire incidents to be less than one every year and another two agencies reported it to be from 1 to 2 every year (referenced tunnels outside the United States were built as early as 1967 to as recently as 2010).

CONSEQUENCES OF FIRE INCIDENTS

Nationally, 17 of 20 tunnels (85%) reported having experienced minor damages without structural damage after a fire. However, there were two episodes of structural damage that required tunnel closure for an extended period of time; New York City's Holland Tunnel and Canada's Lafontaine Tunnel. Only 2 of 20 U.S. tunnels had minor casualties (non-fatal) as a result of a fire. The two casualties reported in the United States were at the Holland Tunnel and in Eisenhower/Johnson Memorial Tunnel. There was one major casualty reported at the Lafontaine Tunnel. (No details on the nature of the casualties were provided.)

SEVERITY OF TUNNEL FIRES

In the United States, in most cases the fire department was involved every time in a fire (15 of 17 responses, 90%). The fire department was involved only occasionally with the Colorado DOT's Eisenhower/Johnson Memorial Tunnel, which has its own fire truck, and has never been involved with the Pennsylvania DOT's Stowe Tunnel, which has so far had no fire incidents. Six of 20 respondents reported that an investigation was performed almost every time after a fire, whereas 8 agencies responded that an investigation was performed occasionally after a fire, depending on its size.

Eight tunnels reported on the estimated maximum fire size, but only one gave an actual numerical answer. The Eisenhower/Johnson Memorial Tunnel (Colorado) provided a fire size of 15–20 MW (51–68 MBtu/hr). The Maryland Transportation Authority's Fort McHenry Tunnel and Baltimore Harbor Tunnel reported a "single tractor trailer truck" fire, and five of the six California tunnels reported a "small car fire."

Four tunnels reported on the longest duration of their fires, with the average of 19 min. The longest fire duration reported was in the Eisenhower/Johnson Memorial Tunnel (25 min).

The international data show that the fire department is involved every time in the fire fighting (four of five responses).

TABLE 9
LIST OF US TUNNEL AGENCIES THAT RESPONDED TO THE SURVEY

Agency	Tunnel Name
Virginia DOT	Hampton Roads Bridge Tunnel—EBL Hampton Roads Bridge Tunnel—WBL Downtown Tunnel (First)—WBL Downtown Tunnel (First)—EBL NAS Runway #29 Underpass Monitor–Merrimac Memorial Bridge Tunnel Midtown Tunnel
Pennsylvania DOT	Liberty Tunnel Stowe Tunnel
Maryland Transportation Authority	Fort McHenry Tunnel Baltimore Harbor Tunnel
Oregon DOT	Oneonta Cape Creek Elk Creek Toothrock Arch Cape Salt Creek Sunset Knowles Creek Vista Ridge Twin Tunnels
Washington State DOT	I-90 Mount Baker Ridge Tunnel I-90 Mercer Island Tunnel
Port Authority of New York & New Jersey	The Holland Tunnel
Chesapeake Bay Bridge and Tunnel Authority	Thimble Shoals Chesapeake Channel
Colorado DOT—Region 1, Maintenance Section 9	Eisenhower/Johnson Memorial Tunnel (2 bores, 1 unit)
California Department of Transportation	Webster Tube Posey Tube Sunrise On Ramp Caldecott Tunnel Complex #1 Caldecott Tunnel Complex #2 Caldecott Tunnel Complex #3

Of the five international agencies responding, three reported that an investigation was performed almost every time after a fire, whereas one responded occasionally, depending on the fire size. The estimated maximum fire size ranged from 1 to 57 MW (3 to 195 MBtu/hr). The longest duration of a fire ranged from 10 min to 120 min (in a Korean tunnel).

EXISTING PRACTICE OF FIRE MANAGEMENT IN ROAD TUNNELS

Most agencies (13 of 19 U.S. tunnels) have been successful and the rest were partially successful in managing fire events. All 22 of the tunnels reporting have an emergency response plan in place. Most agencies have videotaped incidences of car fires.

For all of the national responses, the strengths of the agencies' fire management programs were diverse from equipment, to coordination of multiple entities, to surveillance and rapid response. Preparation and planning were the primary strengths. Of the 19 U.S. tunnels that reported on the kind of fire-detection system used (multiple selections allowed), 18 chose closed circuit television (CCTV) incident detection. Of the 20 U.S. tunnels that reported on the kind of fire protection system used, all chose fire extinguishers in the tunnel, whereas almost all (17) use a standpipe system with fire hose

TABLE 10
LIST OF INTERNATIONAL TUNNEL AGENCIES THAT RESPONDED TO THE SURVEY

Agency	Tunnel Name
Swedish Road Administration	Gota Tunnel
Vägverket (Sweden)	Södra Länken
Mak Hungary (Hungary)	M6 South
Korea Expressway Corporation	Average from 280 tunnels (555 tubes) Jookryung
Ministère des transports du Québec (Canada)	Ville-Marie Lafontaine
Sydney Harbour Tunnel Company	Sydney Harbour Tunnel

connections (dry or wet). Of the 20 responses that reported on the kind of fire life safety system used, all use tunnel ventilation and 9 stated that their tunnel(s) is/are provided with an emergency egress. There is a wide range of communication systems used by rescue personnel and others for fire emergency, the most frequent one being a radio or cell phone (18 of 30 responses). Almost half of the U.S. tunnels reporting (14 of 30) stated that they have tow trucks available for emergency response by either owning them or having the services available in-house. Ten tunnels reported that they contract out for tow trucks.

Only a few of the international agencies reported on the strengths of their agencies' fire management programs or barriers or difficulties that were encountered in implementing fire management. When asked to explain the strengths of the agency's fire management program, two of the four responses (both from Korea) noted that they have a manual procedure, that they are skilled with fire drills, and that they receive feedback from design and construction. Australia's Sydney Harbour Tunnel Company responds with an "immediate use of a deluge system if required." All international agencies reported on the kind of fire-detection system used, where multiple selections were allowed. All seven chose phones, followed by six with CCTV and five with Linear Heat Detection. Of the six that reported on the kind of fire protection system used, all chose fire extinguishers in the tunnel, and five have fire hydrants along the tunnel. Of the seven international agencies that reported on the kind of fire life safety system used, all use tunnel ventilation, followed by six that provide emergency egress. Of the seven international agencies reporting on the communication systems used by rescue personnel and others for fire emergency, two reported using radio repeaters. The rest chose different communication devices, including other types of radios.

BEST DESIGN PRACTICE

Most of the U.S. agencies responding use NFPA 502, matching the FHWA as the most common guidance/standard used by agencies to address the fire design issues for new and retrofitted tunnels. Designers are usually required to follow the NFPA 502 when agencies specify the design fire size and fire curve. Most of the time (9 of 10), designers implemented only security with no blast analysis. A large majority of the responders (28 of 31) do not have a standard for their agency tunnel design and for fire rating.

Many of the responding U.S. tunnel agencies (25 of 31, 80%) consider themselves as the Authority Having Jurisdiction. Usually no risk assessment is approached for fire engineering (20 of 30 responses). State police, fire, or local responders have the role of incident commander (17 of 31 responses).

More than half (16 of 31) would consider protection of the tunnel with the fixed fire suppression sprinkler system to meet the new NFPA 502 maximum fire HRR requirements, if proven effective. Most of the agencies (29 of 31) have not identified gaps in research and design for tunnel fire safety or fire detection and protection. However, Maryland Transportation Authority's Fort McHenry Tunnel and Baltimore Harbor Tunnel reported that commercially available devices/materials to satisfy some code requirements are not reliable or maintainable inside tunnels. These two agencies stated that in eliminating the gaps to improve tunnel fire safety a strategy would be to

> Consider co-development of specifications (industry standards) for the devices along with the fire-code requirements such that reliable and maintainable devices are commercially available that are designed for the tunnel environment. Consider the typical tunnel cleaning/washing operation, chemicals and pollutants

present, and dirt/debris build up. (For example, locating a commercially available pull station system for the roadway tunnel application that is reliable over a long time period has proven difficult).

Many of the U.S. tunnels (22 of 29) would consider a fire event to be similar to a seismic event for design purposes.

Most international agencies, four of the seven reporting, have their own standard for tunnel design and for fire rating. All five international respondents stated that the most common guidance/standards used by designers to address the fire design issues for new and retrofitted tunnels were either domestic regulation, European Union, or PIARC. In Canada they use NFPA 502. Four of seven responded that designers are usually given only the fire size, whereas three are providing the fire curve. Two of the six international agencies to respond reported that designers usually implement only security, followed by two respondents noting that they implement security and blast design.

One-half of the international agencies reported that the Authority Having Jurisdiction is usually the fire department. All seven international agencies responding reported applying a risk assessment approach for fire engineering. This is probably the most obvious difference between the U.S. and international approaches. Five of the seven respondents reported having an emergency response plan in place.

Of the six international agencies responding on which agency has the role of incident commander, two reported the fire department and two that it is in cooperation with the fire department. Four of six international tunnel agencies reported that they would consider protection of the tunnel with the fixed fire suppression system (sprinkler system) if proven effective. Most of the agencies (four of six) have identified gaps in research and design for tunnel fire safety or fire detection and protection. One area needing improvement, according to one agency, is "Real world experience in the use of deluge." Most of the international tunnels (five of six) would not consider a fire event to be similar to a seismic event for design purposes.

MAINTENANCE, REPAIR, AND REHABILITATION OF THE FIRE MANAGEMENT SYSTEMS

The average tunnel age as given by the 32 U.S. tunnels was approximately 54 years (built around 1956). Most tunnels are under 24 h supervision (21 of 32 tunnels reported). The majority of the tunnels reported that the normal traffic operation is uni-directional (28 of 32). Thirty-four percent (11 of these 32) reported that their tunnel operates in bi-directional mode only during construction/maintenance in the other tube and 16 never run in bi-directional mode. Eight U.S. tunnels allow gasoline tankers to run freely and four tunnels can be used by gasoline tankers when supervised and during special times (schedule or tunnel closing).

Twenty-four tunnels responded to what is an acceptable response time for a fire emergency, and answers ranged from 3 to 20 min. All seven VDOT tunnels considered 10 to 15 min acceptable, whereas all nine Oregon DOT tunnels considered 20 min to be an acceptable response time. The lighting and emergency communication systems were often not designed to survive major fire events (17 of 30). One-half of the 30 tunnels reported that they were inclined to actively screen or otherwise monitor truck cargoes entering a tunnel without disrupting the traffic flow as a prevention method. Of the eight that responded with the most common fire or life safety equipment planned for repair or replacement, all responded with tunnel ventilation, standpipes, and communication. The next most common choice was emergency lighting (six responses).

The average of the 20 U.S. tunnels that provided a numerical life expectancy was 105 years. VDOT noted that for its seven tunnels their "design life is 50 years, however, life expectancy typically exceeds 100 years." The Chesapeake Bay Bridge and Tunnels stated for both of their tunnels that it "depends on the amount of maintenance performed."

Most U.S. agencies (19 of 31, 61%) reported on the need for additional training tools for operators to manage a fire using tunnel fire/systems simulators.

Outside of the United States, and excluding Korea's "average from 280 tunnels," the average age is approximately 16 years (built about 1994). All seven international agencies reported that their tunnels are under 24-h supervision. (Please note that there are many unmanned tunnels all over the world and the above number does not reflect all of the existing tunnels.) Six of the seven international agencies stated that their tunnels run uni-directional during normal traffic operation. Four of the six international tunnels reported that their tunnels never operate in bi-directional mode. The rest normally do operate in bi-directional mode. As for what types of vehicles use the tunnel, five of seven tunnels reported HGVs and four reported gasoline tankers (freely).

Internationally, there was a broad spectrum of tunnel life expectancy. Three of the seven tunnels chose 100 years and two chose 50 to 100 years. The other two agencies reported 200 years and 80 years.

Two of the six international tunnel agencies reported that 10 to 15 min is an acceptable response time for reaching a fire event. The remaining four reported 2 to 10 min. Five of the six agencies reported that the lighting and emergency communications systems were designed to survive major fire events most of the time.

Five of the six tunnels do not actively screen or otherwise monitor truck cargoes entering the tunnel without disrupting the traffic flow.

Seventy-two percent of national and international tunnels are under 24 h supervision, 87% reported that their tunnels operate uni-directionally, whereas 52% never operate in bi-directional mode, even if there is construction and maintenance in the other, parallel tube. Gasoline tankers are freely allowed in 42% of national and international tunnels, whereas only four allow them to travel with supervision when the tunnel is closed to normal traffic (none of the international tunnels). Fifty-five percent of the national and international tunnels reported that they do not actively screen or otherwise monitor truck cargoes entering the tunnel without disrupting the traffic flow, whereas the remaining 45% reported that they do.

Sixty percent of the tunnels reporting worldwide noted that they need additional training for operators to manage a fire utilizing tunnel fire and systems simulators.

SELECTED IMPORTANT EXAMPLES

Among all the tunnels responding, the Port Authority of New York & New Jersey's The Holland Tunnel, built in 1927, was one of the two tunnels that reported suffering structural damage as a result of a fire that required tunnel closure for an extended period of time. It was also one of the two that reported minor casualties. It was the only tunnel reporting two to five vehicle fire incidents per year. The most severe vehicle fire incidents in this tunnel were from a passenger car, a heavy goods truck, vans, and a truck load of magnesium in 1948. In The Holland Tunnel, the fire department is involved every time and investigations have been performed occasionally depending on the fire size. There is no information on its estimated maximum fire size or its duration. Continuous training has been suggested.

The Holland Tunnel uses pull stations, CCTV, telephones, and linear heat detection in its fire-detection system. The fire protection system in the tunnel involves fire extinguishers, fire hydrants, fire apparatus, and a wet standpipe system with fire hose connections. The fire life safety system involves tunnel ventilation and an emergency egress. It was reported that periodic hot smoke fire tests are conducted in the tunnel to train the operators and verify system performance. They believed that a tunnel fire/systems simulator would be useful for operators to help manage a fire.

Other U.S. tunnels of interest are the Colorado DOT Eisenhower/Johnson Memorial Tunnels, built in 1973 and 1979, respectively. Although it only had minor damages (no structural damage), it was one of the two that reported minor casualties. It reports having one to two vehicle fire incidents per year. The most severe vehicle fire incidents in this tunnel were from recreational vehicles and motor homes. The fire department is involved occasionally for both tunnels and investigations have been performed every time. The estimated maximum fire size was 15–20 MW (51–68 MBtu/hr) and the longest duration was 25 min. The Eisenhower/Johnson Memorial Tunnels reported one barrier or difficulty encountered when implementing fire management, where there were technical issues regarding minimal emphasis on training. The tunnels use only CCTV for its incidence (fire) detection system. The fire protection system in the tunnel involves fire extinguishers, fire hydrants, and a fire apparatus. The fire life safety system involves tunnel ventilation and an emergency egress. They believed that a tunnel fire/system simulator would be needed for operators to help manage a fire.

Among the international examples selected were Québec's Ville-Marie & Lafontaine Tunnels, built in 1976 and 1967, respectively, and the tunnels combined their responses. The fire incident occurred in the Lafontaine Tunnel in 1982. This tunnel fire was caused by a heavy goods truck and there was one fatality. Structural damage in the Lafontaine Tunnel required tunnel closure for an extended period of time (about 2 months). The combined data for the Ville-Marie & Lafontaine Tunnels noted one to two vehicle fire incidents per year. The most severe vehicle fire incidents were from heavy goods trucks. The fire department was involved every time and investigations were done occasionally, depending on the fire size. The estimated maximum fire size was 20 MW (68 MBtu/hr) and the longest duration was 30 min. The tunnels use telephones, video surveillance technology, and 911 for its fire-detection system. The fire protection system in the tunnel involves fire extinguishers and fire hydrants. The fire life safety system involves tunnel ventilation and emergency egress. They believed that a tunnel fire/system simulator would be needed for operators to help manage a fire.

Australia's Sydney Harbour Tunnel, built in 1992 with a life expectancy more than 100 years, is protected by a fixed fire suppression system. For fire detection, this tunnel uses CCTV, telephones, heat detection (other than linear), tunnel smoke detection, and video surveillance technology. For fire protection, this tunnel uses fire extinguishers and fire hydrants in the tunnel; a fire sprinkler system, a fire apparatus, and foam are stored in the tunnel. For fire life safety, this tunnel uses tunnel ventilation, an emergency egress, and an egress pressurization system. A waterscreen displaying a 7×4.5 m (23×14.8 ft) stop sign is used to minimize or eliminate problems such as congestion and traffic management during a fire. Cars, buses, trucks, and HGVs use this tunnel, and there is an average of less than one vehicle fire incident each year. The fire department is occasionally involved in fire fighting and there is an investigation after each fire. A passenger car fire was considered to be the most severe vehicle fire incident. A deluge sprinkler was used in managing the fire event. Although this incident caused no damage to the tunnel, it was closed for operation for more than 30 min. There were no casualties. The estimated maximum fire size was 3 MW (10 MBtu/hr) and lasted 10 min. There are various exercises and other training provided to staff and first responders to ensure proficiency in response to an incident. They "burn cars in the tunnel to demonstrate the smoke, heat and noise to our operators. This also enables the deluge and ventilation to be proven. All operators have to complete task books on a regular basis." Tunnels and emergency response equipment are inspected and tested every 6 months. The operational protocols for the use of the ventilation system during a fire event are "preprogrammed for a single fire, multiple fire and congested tunnel."

FINDINGS AND FUTURE STUDIES

Responses were received from 15 agencies representing 319 tunnels worldwide. Nine U.S. agencies reported on a total of 32 tunnels, whereas 6 international agencies reported on a total of 287 tunnels worldwide (280 from Korea's average).

The questionnaire proved that fires in road tunnels are rather rare events, with a greater number of fires occurring in the busiest tunnels. In most of the U.S. tunnels, fires happen one or two times a year; however, most of them are small and do not result in any significant issues. The most significant fires occur with trucks (HGVs). In these cases, casualties are likely. In 1948, the Holland Tunnel in New York and the Lafontaine Tunnel in Canada experienced structural damage after a fire and had to close for an extended period of time. Other tunnels have never experienced structural damages and/or lengthy closures. The maximum estimated fire HRR was reported at 57 MW (195 MBtu/hr). Typically, fire departments are involved in serious fire events and investigations follow most of the time.

Based on the responses received to our survey, it takes about 30 min to extinguish a severe tunnel fire; however, the longest reported event lasted for 120 min. Most of the tunnels are equipped with CCTV cameras and have videotapes of fire incidents. Almost all of the tunnels have an emergency response plan.

Most of the U.S. agencies and some international agencies rely on NFPA 502 for tunnel safety design. International agencies also use PIARC, the European Union, and other documents for guidance. Several international agencies provide the designers with fire curves along with the fire size. All seven of the international agencies apply a risk assessment approach for fire engineering, whereas only 10 of the 30 U.S. tunnels reported applying a similar approach. Most of the national and international agencies responded that they would consider a fixed fire suppression system to meet the new NFPA 502 Max Fire HRR Requirements, if proven effective. Some stated that they are looking for real-world experience in the use of a deluge system.

More than 60% of the tunnel agencies reporting worldwide expressed their interest in additional training tools for operators to manage fires using a tunnel fire systems simulator. One recommendation that came from most of national and international responders is the need to develop computer-based training tools for operators to manage fires using a tunnel fire systems simulator. Preparations and planning and emphasis on training are considered to be the most important. This is one of the areas that require future studies and development. Fire drills and having feedback from design and construction are considered the strength of the agency's fire management programs.

Another lesson learned is that many agencies (55% of those responding worldwide) would consider protecting tunnels with the fixed fire suppression system (sprinkler system) if proven effective. Future studies are required to address this area of technology for tunnels.

Most of the agencies rely on CCTV for fire detection and incident detection. This technology needs to be further developed for heat and smoke detection, as well as be tested and listed for tunnel fire-detection applications.

All responders rely on tunnel ventilation systems for heat and smoke control. There is a need to continue developing such ventilation systems and ventilation response in conjunction with other systems such as fixed fire suppression systems.

Specifications are needed for the devices that require further development. Reliable and maintainable devices could become commercially available that are designed for the tunnel environment, considering the typical tunnel cleaning/washing operations, chemicals and pollutants present, and dirt and debris build-up. One example is locating a commercially available pull station system for a roadway tunnel that has long-time reliability.

Although many U.S. agencies prohibit gasoline tankers from entering tunnels freely (8 of 32 tunnels allow them), they are allowed freely in most of the international tunnels. Four U.S. tunnels allow gasoline tankers to travel through while supervised and when the tunnel is closed to normal traffic. Their experience may need further study.

Although most 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 considered for fire design for most uni-directional tunnels.

COMPUTER-BASED TRAINING TOOLS FOR OPERATORS TO MANAGE FIRE—VIRTUAL TRAINING

Survey results demonstrated the need for computer-based training tools. The training of emergency service personnel and tunnel operators is an important aspect in ensuring the safety of tunnels. Often, such training is hampered by the limited training opportunities. For the training of firefighters, tunnels either have to be temporarily closed or special underground facilities have to be used. Also, there is the additional environmental issue of making fires, which are generated by burning cars or by pan fires. Finally, such exercises may damage or dirty the tunnel. Virtual training offers a user-friendly and clean alternative. In a virtual training tunnel, fire and smoke only exist in computer memory. Virtual exercises have many advantages, including that they:

- May be repeated as often as necessary,
- Do not require the closure of tunnels, and
- Do not cause pollution.

The VIRTUALFIRES simulator has been developed within a European project and allows the user to visualize the fire and smoke development and the transport of heat and toxic combustion products inside a tunnel and then move through the virtual space in the same way as through a real, physical tunnel (*13*). The simulator uses and accesses a database, which contains the results of 3D transient combustion (CFD) simulations for particular tunnel geometries with associated safety installations, particular fire hazard scenarios, and so forth. The CFD results can be displayed using a personal computer and a head-mounted display.

Two systems have been developed. The first where the CFD simulation is pre-calculated, stored in a database, and then displayed. The other's calculations are carried out in parallel to the visualization. In the first system, the user will be able to move through the data, but will not be able to change the characteristics of the simulation such as the ventilation characteristics in real time. In the second system, the user may change the properties of the simulation while the data are displayed and observe a real-time effect of the changes.

The VIRTUALFIRES simulator can be used for assessing the fire safety of tunnels, for the training of rescue personnel, and for planning rescue scenarios, and will be able to supplement real fire tests. The end users of this system are rescue organizations such as fire departments, tunnel operators, and government organizations interested in tunnel safety. The system can be used for making an objective assessment of the fire safety of existing tunnels. It can also be used for educating drivers on how to behave in case of a fire emergency in a tunnel and what to expect.

The VIRTUALFIRES system is able to handle tunnels of any cross section with a variety of installations, including:

- Fans;
- Ventilation inlets and outlets;
- Fire extinguishing nozzles;
- Escape compartments, exits, lights etc.; and
- Cars, trucks, or rolling stock.

The data describing the shape of the tunnel cross section as well as the fixed installations are provided in a suitable format (AUTOCAD) and are used to generate the grid for the transient combustion calculation.

The user may:

- Define a scenario and replay this scenario using the forward/stop/rewind/start buttons on the graphic user interface.
- During a concurrent session, the user may switch on/off existing fans, fire extinguishers, and restart a session.

The following can be visualized:

- Smoke (using output from the CFD software) to check visibility.
- Iso-surfaces of temperature to check survivability.
- Streamlines allowing for visualization of the efficiency of the ventilation system.

One of the goals of a project was to achieve real-time CFD calculations so that users may immediately see the effects from changes, such as from switching on/off fans and from activating fire extinguishers.

The calculated dataset consists of different ventilation scenarios for the Mt. Blanc Tunnel in France and the Gleinalm Tunnel in Austria. Both tunnels were examined with their former ventilation systems and also with the improved ventilation systems after reopening.

Another tunnel simulator was developed in Sweden and has been in operation since the summer of 2004. It is an important instrument for creating realistic conditions to help train operators to better handle fire situations. With this simulator, the Swedish Road Administration can maintain a high level of staff competence without causing disruptions in traffic that usually result from major exercises in tunnels. One of the major goals is to provide the training in a useful and cost-effective way.

The simulator is also used to evaluate existing routines and checklists for the Göteborg tunnels. Through the simulator, errors and weak spots in the routines can be found before they have an actual impact in the real world (see Figure 13).

New tunnel simulators can also be developed and tested on the design stage before they are introduced into the traffic environment, so that operators will be well prepared when a new tunnel opens. In Sweden, all future tunnel projects will require a tunnel management application utilizing the simulator. The simulated tunnel environment was in use for two months before the opening of Göteborg's latest tunnel, the Göta Tunnel. This gave the traffic managers ample time to acquire experience with the new system before the opening. With periodic updates on various situations, they are better prepared when an incident occurs. Groups of operators from various tunnels gather after training sessions to discuss the

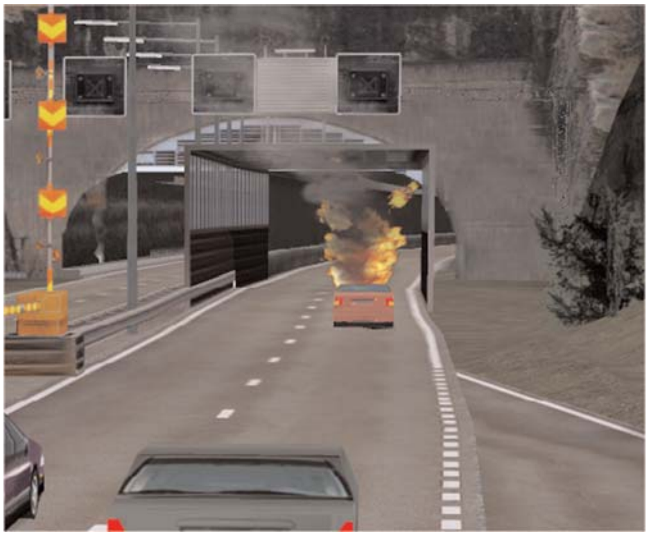

FIGURE 13 New tunnel simulators.

taught scenario. In this way they can learn from each other. The simulator is also used for training new operators; it helps to familiarize them with how the tunnel monitoring application works before they work on a real one. The simulator can also be extremely beneficial for existing tunnels.

In the simulator, the tunnel and its vicinity are modeled using a 3D modeling tool, creating a virtual version of the tunnel. The model is then filled with vehicles. Despite its complexity, the tunnel simulator can be run on a regular computer, without the need for upgraded hardware. The detailed graphics are created using normal graphic cards and an industry standard 3D graphics engine.

The VIRTUAL FIRE project, discussed earlier, was developed as a computer-based training tool. It is important to establish a similar program for the United States and to incorporate this tool into the U.S. standards.

CHAPTER NINE

DESIGN FOR TUNNEL FIRES—LITERATURE REVIEW

BACKGROUND

Every tunnel is unique, making it difficult to generalize designs for road tunnel fires. As reported, design fires and design fire scenarios are essential inputs for a fire safety-engineered approach to fire safety design of new tunnels and any appraisal of fire safety protection measures in existing tunnels. An effective fire protection design for life safety and property protection in tunnels requires a systematic assessment of a number of component “sub-systems,” which contribute to the overall safety of the design. These sub-systems are:

- The initiation and development of fire spread
- Spread of smoke and toxic gases
- Detection of fire and activation of active fire life safety systems
- Tunnel users’ evacuation
- Fire service intervention.

Further complexity arises because the time scales for the response of active fire protection measures such as fire detection and safety systems activation are different from the response time of occupants during evacuation or the response time for structural integrity.

The first priority identified in the literature for fire design of all tunnels is to ensure:

1. Prevention of critical events that may endanger human life, the environment, and the tunnel structure and installations.
2. Self-rescue of people present in the tunnel at time of the fire.
3. Effective action by the rescue forces.
4. Protection of the environment.
5. Limitation of the material and structural damage.

Furthermore, part of the objective is to reduce the consequences and minimize the economic loss caused by fires.

A 100% safety scenario against a tunnel fire is not possible; however, actions can be taken to reduce the risk to a reasonable minimum. Preventive measures are safety measures that reduce the probability of an unwanted event. Preventive safety measures in tunnels can be related to:

- Organization and traffic management;
- Structural or geometrical solutions; and
- Safety equipment, such as heat detection of vehicles before entering the portals.

Preventive measures on fire in a tunnel are related to

- Removal of sources of ignition,
- Reduction of the likelihood of a fire, and
- Prevention of the development from the ignition to a severe fire.

Gasoline tankers are prohibited from using many U.S. tunnels. Dangerous goods that travel through tunnels can be costly in terms of human lives, tunnel damage, transport disruption, and the environment. Conversely, needlessly banning dangerous goods from tunnels may create unjustified economic costs and force transport operators to use more dangerous routes.

The fire prevention measures presented in Table 11 can be implemented in tunnels to reduce either the probability or the consequences of an incident in a tunnel.

The main engineering goals regarding the fire protection of road tunnels are listed here in order of priority, as identified in the literature:

1. Objectives related to life safety:
   - Minimize the risk of injury or death for tunnel users in the event of a fire.
   - Minimize the risk for people outside of the tunnel.
   - In densely populated areas, people outside the tunnel may also be affected by the fire inside the tunnel (e.g., when buildings are present above the tunnel or when dense and toxic smoke may cause secondary incidents on roads adjacent to the tunnel).
   - Minimize the risk of injury or death for rescue teams and repair workers.
2. Objectives related to economic consequences and to the quality of life:
   - Avoid damage that threatens the tunnel construction.
   - Avoid the need to incur expensive repair work.
   - Avoid long-term interruption of service.

The proactive measures comprise all of the general actions taken in the planning phase to improve tunnel safety—independently of a specific tunnel project.

TABLE 11
RISK REDUCTION MEASURES CLASSIFIED ACCORDING TO THEIR MAIN PURPOSE

Measures to Reduce the Probability of an Accident *Related to tunnel design and maintenance*		
Tunnel cross section and visual design	Alignment Lighting (normal)	Maintenance Road surface (friction)
Related to traffic and vehicles		
Speed limit Prohibition to overtake	Escort Distance between vehicles	Vehicle checks
Measures to Reduce the Consequences of an Accident *Alarm, information, communication of operator, and rescue services*		
Closed-circuit television Automatic incident detection	Automatic fire detection Radio communication (services)	Automatic vehicle identification Emergency telephone
Communication with users		
Emergency telephones Radio communication (users)	Alarm signs/signals	Loudspeakers
Evacuation or protection of users		
Emergency exits Smoke control	Lighting (emergency) Fire-resistant equipment	Failure management
Reduction of accident importance		
Fire-fighting equipment Rescue teams	Drainage Road surface (non-porous)	Emergency action plan Escort
Reduction of the consequences on the tunnel		
Fire-resistant structure	Explosion-resistant structure	

Source: *Safety in Tunnels* (2001) (*41*).

- Legislative initiatives and other actions highlight the awareness of the problem and contribute to an improvement in the standards for designing and operating tunnels.
- Research projects and similar actions that develop and disseminate knowledge about tunnel fires contribute to future tunnel safety.
- In addition, any proactive measures regarding user behavior such as an increase in awareness to safer driving and correct behavior in the event of an incident may significantly influence safety in the tunnel.

Mitigation measures are safety measures that aim to limit the consequences once the ignition has taken place and developed into a fire. The mitigation measures may be related to:

- Reduction of the fire development,
- Reduction of the consequences to humans, and
- Reduction of the consequences to structure and equipment.

Reduction of Fire Development

Structural Measures

Flammable liquids may leak during or before a fire. A suitable drainage system reduces the quantity of flammable liquids from the source of the fire and thereby mitigates a serious fire development.

Safety Equipment

- The main function of ventilation during a fire is to control the smoke and, to some degree, influence the development of the fire.
- Fixed fire suppression systems can prevent fires from developing into severe fires, but could reduce visibility in the tunnel.

The best chances of successful fire fighting are in the initial phase of a fire. Therefore, systems directed by operators or end users may be beneficial. Such installations are easy to use because the tunnel's users will probably be unfamiliar with fire fighting and with the tunnel's environment.

Response to Fire

The fire resistance of doors and walls reduce the probability of the development and spread of fires from one compartment to another. The fire resistance of the active fire life safety systems (e.g., ventilation and fire suppression) ensures that the development of the fire can be controlled.

Reduction of Consequences to Humans

Structural Measures

The highest priority of tunnel design safety is to mitigate consequences to humans. The geometrical layout of a tunnel can contribute to the mitigation of a fire. For example, it is easier to ensure that the majority of tunnel users have smoke-free conditions if the tunnel is operated in one-way traffic. Also, the cross-sectional area influences the chances of creating smoke-free areas and providing conditions for escape from a fire.

One of the most important mitigation measures for users exposed to a fire in a tunnel is the provision of escape routes. Safety will be influenced by the spacing and design of the emergency exits. In some cases, the rescue and evacuation of the injured and physically disabled will have to be assisted by the rescue forces, tunnel operators, etc. Emergency exits can serve as access routes for the rescue forces.

Safety Equipment

The ventilation system is a crucial safety measure when a fire occurs, because it allows for smoke-free escape routes. The ventilation system is designed to control the smoke spread, and this can be achieved by blowing smoke in one direction, supporting smoke stratification and extracting smoke at the ceiling or near the ceiling, or blowing smoke in one direction and extracting it at a few places.

Alarm systems including telephones, push buttons, pull boxes, detection, and surveillance are important to alert the operator and thereby activate the emergency procedures, ventilation systems, etc. Unfortunately, those systems are seldom utilized by tunnel users. In 46 tunnel fire incidents in Austria, the emergency telephone was used only 10 times (22%). Pull boxes/push buttons were used only four times (9%) (*42*).

Communications systems influence the evacuation of the tunnel during a fire and thereby reduce the number of people at risk by exposure. The communications systems can be radio re-broadcast (audio warning) and message boards (visual notification). Once the evacuation has been initiated, it is important that the tunnel users reach the safe area as quickly as possible. Exit signs, exit route guidance, lighting, and markings are mitigation measures that can make the escape more efficient. All these elements are discussed in details in the NFPA 502.

Response to Fire (Fire Resistance of Safety Systems)

It is particularly important that the installations necessary during an emergency continue to function for a suitable duration during a fire.

Reduction of Consequences to Structure and Equipment

Safety Equipment

Fire suppression systems can potentially prevent severe damages to the structure and to the equipment once activated at an early stage of fire development. It is possible to have fixed installations in the traffic space to suppress fires in vehicles or other sources. Often, the purpose of the fixed suppression installations is not to extinguish the fires but to control and limit fire development. (See Annex of NFPA 502 2008 edition for additional information.)

Response to Fire: Structural Fire Resistance and Fire Protection

One of the serious consequences of a fire is damage to the tunnel structure and its ultimate collapse. By suitable design of the tunnel structure and by passive fire and/or fixed fire suppression protection, the tunnel can withstand the relevant fire scenario and tunnel rehabilitation and repair costs can be reduced or eliminated.

Fire Resistance of Equipment, Power Supply, and Cabling

The installations are often the first part of the tunnel system to suffer damage in a fire. By suitable design and passive or active fire protection systems the damage to the installations can be reduced. The cabling and other installations are protected to resist fire damage. Safety critical equipment in road tunnels must be able to function in the event of fire. The physical location, such as a lower level, may also reduce fire damage. Different countries have different requirements for the equipment. For example, a minimum temperature requirement in the NFPA 502 for the tunnel ventilation fans, dampers, and sound attenuators is 250°C (482°F) for 1 h of exposure. A higher temperature is used depending on the results of the calculations. Many international standards have requirements of 250°C (482°F) for 90 min of exposure and a maximum of 400°C (752°F).

The development of emergency response plans requires a consideration of activities before, during, and after the incident, and covers:

- Prevention and training,
- Accident management, and
- Fire emergency operations.

INTEGRATED APPROACH TO SAFETY IN TUNNELS

Safety is a result of the integration of the infrastructural measures, the operation of the tunnel, and user behavior, as well as preparedness and incident management. The assessment of fire safety in tunnels is a complex issue, where broad multi-disciplinary knowledge and application of different physical models are necessary to explore the causes and development of fires to evaluate measures to prevent and reduce their consequences. In general, an overview of the entire system is necessary to determine the best possible actions (*43*).

The systems to take into account comprise:

- The occurrence and physics of fire development.
- The tunnel systems; that is,
  - Infrastructure and
  - Operation.
- Human behavior of users, operators, and emergency services.
- Other factors influencing safety.

Prescriptive Approach

Traditionally fire safety standards for tunnels and other structures have been prescriptive; they have contained minimum requirements that must be fulfilled. These requirements have been established over the years based on experience, tradition, and engineering/expert judgment. They apply in principle by absolute evaluation of safety: if the design is in accordance with the standard, the safety is acceptable; if not, it is unacceptable. The advantage of a prescriptive standard is that it is not difficult to use and it ensures a minimum level of requirements. On the other hand, prescriptive standards may not be applicable to unusual situations and in some cases may not be able to take into account the interaction between different parts of the tunnel structure, installations, and the local conditions.

Performance-based Approach

In recent years, the national and international standards have tended to favor the performance-based approach. NFPA 502 is not an exception. By application of fire performance concepts, fire safety is achieved based on a scientific understanding of the fire phenomena, of the effects of fire, and of the reaction and behavior of people. Emphasis is given to the safety of life, whereas fire safety engineering can also be used to assess property loss, interruption of service, contamination of the environment, etc. Furthermore, risk of fire and its effects are quantified and the optimum safety measures are evaluated.

By a performance-based approach, the regulatory requirements are given on a more general level specifying the safety of the users, economic values, and so forth. This may result in different interpretations leading to undersized fire and underdesigned safety systems.

Fire safety engineering will normally involve the following steps:

- Qualitative design review:
  - Definition of objectives and safety criteria, with reference to performance-based standard requirements and coordination with the authorities having jurisdictions;
  - Definition of the tunnel system;
  - Identification of fire hazards;
  - Selection and definition of fire scenarios;
  - Identification of methods of analysis; and
  - Identification of design options.
- Quantitative analysis of design using the appropriate subsystems:
  - Fire ignition, development of heat and smoke;
  - Spread of fire, heat, and smoke;
  - Structural response to fire;
  - Detection, activation, and suppression; and
  - Behavior of tunnel users and influence of fire on life safety.
- Assessment of the outcome of the analysis and evaluation against criteria.

The objectives and the associated acceptance criteria used in a performance-based approach is clearly defined and established for the particular design. The acceptance criteria, which establish the adequacy of the design, can be according to the following approaches:

- Deterministic (including, when appropriate, safety factors).
- Probabilistic (risk-based used in European countries).
- Comparative (comparison of performance with accepted codes of practice).

The deterministic and the comparative approaches are to some extent similar to the prescriptive approach, but allow for more flexibility. The performance-based approach generally requires more data and procedures resulting in a more complex and time-consuming design. For the designer, a prescriptive approach is an advantage with respect to liability.

A design fire is an idealization of a real fire that might occur. A design fire scenario is the interaction of the design fire with its environment, which includes the impact of the fire on the geometrical features of the tunnel, the ventilation and other fire safety systems in the tunnel, occupants, and other factors.

Nobody can precisely predict every fire scenario given the range of variables and human behavior. It is not known

- What will cause the fire (collision, electrical problem, terrorism)?
- What exactly will be burning (goods, furniture, car body, etc.), including the number of vehicles involved in the fire?
- Where will (in which part of the tunnel) the fire occur?
- When will the fire start (month, time of the day, etc.)?
- What the outside environmental conditions will be at the time of incidence (winds, hurricane, earthquake)?
- What will be the traffic conditions?
- How will the tunnel users' behave in an emergency?
- How will the operators behave during an emergency?

Therefore, the designer makes a number of assumptions to ensure that the design will save lives and retain structural integrity under most of the foreseeable fire scenarios.

International standards on preventive fire protection are based on a risk approach. In a European study, it was found that risk estimates produced by different users differed by "several orders of magnitudes." The estimates varied significantly from case to case. Serious concerns on risk analysis have recently been found in the Channel Tunnel design that has already experienced several large fire events since its opening.

The PIARC report reiterates the need for a greater focus on the definition of appropriate fire scenarios dealing with specific aspects of tunnel fire safety. This can be achieved by accurate specification of the input and output characteristics of design fires.

The main cause of death in a fire is related to inhalation of smoke and hot gases and not from the fire itself. Therefore, with respect to life safety, attention is given to the determination and mitigation spread of (possibly toxic) hot gases and smoke. Some key design fire scenarios relevant to the fire safety in tunnels are listed here:

1. Design fire scenario for ventilation and other systems (e.g., fixed fire suppressions) design and assessment—Smoke ventilation in tunnels needs to be designed on

the basis of smoke flow rates (i.e., the volume flow in the fire plume) using a design fire and local gas temperatures downstream from the design fire because they determine the ventilation volume flow rates. The design fire scenario takes into account all the important issues such as a time factor, ambient conditions, wall properties, and the efficient operation of detection and ventilation systems, which can have a significant influence on the appropriate design fire characteristics.

2. Design fire scenario for egress analysis—Evacuation measures for tunnel users or emergency rescue services need to be within tenable environmental conditions, identified as breathable gas temperatures and concentration of toxic gases at head height in the tunnel, as well as hot gases at higher levels in the tunnel that radiate down onto evacuees. A tenable environment is well-defined in NFPA 502. Time is a very important factor. The times for hazardous conditions to develop at particular locations as discussed later in this chapter need to be compared with occupant egress times. These in turn need to take into account the time it takes for occupants to realize they are in danger and begin their escape. Evacuation time from buses also needs to be considered.
3. Design fire scenario for thermal action on structures—See time–temperature curve discussion.
4. Design fire scenario for the safety of tunnel fire equipment—Usually the critical fire life safety equipment is required to be designed for the expected environment during a fire emergency.
5. Design fires for work on tunnel construction, refurbishment, repair, and maintenance—Fires related to, for example, tunnel boring machines and the refurbishment of tunnels are considered out of the scope of this report.

Based on the tunnel experience and tunnel fire tests, several observations can be made:

- Each tunnel is unique
- A tunnel is a risky environment. No tunnel is absolutely safe regardless of how it was designed. The designer's goal is to make it as safe as possible based on previous experience, on current knowledge, and on technical equipment development. Consequences of tunnel fires can be disastrous.
- Tunnels are generally safe. Tunnel fires are rare events and happen less often than fires on open roads. Fewer than 150 people have been killed anywhere in the world in road tunnel incidents involving a fire—and that includes those killed by any preceding accident (*44*) (collisions). Fewer than 20 tunnels around the world have suffered substantial damage as the result of a fire emergency.
- Road tunnel fires cannot be completely eliminated until vehicle fires are eliminated.

DESIGN FIRE SIZE

Design fire size is one of the most important parameters for tunnel fire engineering. The materials that burn in a fire mostly come from the vehicles involved, and they include elements of the vehicles, such as the seats, tires, plastic materials in the finishing or even in the body work itself; cargo; the fuel from the vehicle tanks, which amounts to hundreds of gallons for trucks; and the loading, especially for goods vehicles. The goods loadings vary and can lead to many different kinds of fires. Some examples of combustion energy outputs are given in Table 12.

For design purposes it is necessary to choose fire characteristics corresponding to the traffic that uses a particular tunnel. Conditions, such as the allowance of transporting hazardous vehicles and materials, have to be taken into account.

Tunnel fires differ from open fires in at least two important ways:

1. The heat feedback of the burning vehicles in a tunnel fire tends to be more effective than that in an open fire because of the confined enclosure. This effective heat feedback often causes vehicles that do not burn intensely in an open fire to burn vigorously in a tunnel fire. For

TABLE 12
EXAMPLES OF COMBUSTION ENERGY OUTPUTS

Type of Vehicle	Approximate Energy Content [MJ (MBtu)]	Remarks
Private Cars	3,000–3,900 (2.8–3.7)	Used for fire tests in Finland
Private Car	6,000 (5.7)	Used for EUREKA fire tests
Plastic Car	7,000 (6.6)	
Public Bus	41,000 (39)	
Heavy Goods Vehicle (HGV)	88,000 (83)	
Loads for HGV	67,000 (63.5)	Used in the fire tests in the
	129,000 (122)	Runehamar Tunnel
	152,000 (144)	
	240,000 (227.5)	
Tanker with 50 m^3 Gasoline	1,000,000 (948)	Medium tanker
	1,500,000 (1422)	Dutch assumption for a lar ge" design fire

Source: PIARC (*21*).

example, Beard and Carvel (*35*) concluded that the HRR of a fire within a tunnel could increase by a factor of 4 compared with that of the same material burning in the open. Furthermore, the oxygen needed for combustion is not always as readily available in tunnels as in the open (depending on the tunnel geometry and fire size). The fire conditions may either develop to a:

– Fuel-controlled fire where unreacted air bypasses the burning vehicles (typical tunnel fire controlled by limited fuel available), or a
– Ventilation-controlled fire, giving rise to large amounts of toxic fumes and products of incomplete combustion. Essentially, all the oxygen is consumed within the combustion zone and fuel-rich gases leave the exit of the tunnel (e.g., extremely severe tunnel fires, such as the Mont Blanc fire where oxygen is limited).

2. As a fire develops in a tunnel, it interacts with the ventilation airflow and generates aerodynamic disturbances in the tunnel flow. This interaction and disturbance may lead to drastic changes in the ventilation flow pattern, such as throttling of airflow (buoyancy effects) and reverse flow of hot gases and smoke from the fire into the ventilation air stream (backlayering). Such effects on the ventilation not only complicate firefighting procedures, but also present extreme hazards by propagating toxic fumes and gases far from the fire. Impact of ventilation on fire size is discussed in chapter thirteen.

Design fires in tunnels are usually given as the peak fire HRR. There are various methods and techniques to calculate and estimate the fire HRR of a given vehicle; some could be provided by manufacturers (for cars and buses), others calculated; however, there is no common ground on how to calculate the HRR. One method is the weighting of the burning components of a vehicle, another is analytical. Some calculations incorporate burning efficiency, which means that the fire may not consume the entire heat load available. The leftover content is typically in the form of either a char residue or as soot and smoke particles displaced by the combustion gas stream (*45*).

The magnitude and development of fire depends on:

- Vehicle combustion load (often called the fuel load, which is usually greater than the potential fire size),
- Source of ignition,
- Intensity of ignition source,
- Distribution of fuel load in the vehicle,
- Fire propagation rate,
- The tunnel and its environment (including available oxygen), and
- Other factors that will be discussed in the following chapters.

The fire power is measured in megawatts (MW) or MBtu/hr (1,000 Btu/hr), although it has become more common for engineers to combine the peak HRR with the fire growth rate. For example, full-scale tests of HGV loads in the Runehamar Tunnel showed that the HRR can exceed more than 100 MW (341 MBtu/hr) in less than 10 min. This means that the fire growth rate will be crucial in determining whether those caught in the fire can escape. Studies showed that the fire growth rate is more important than the peak HRR when investigating the safety of people in the tunnel. The peak HRR varies between 1.5 MW (5 MBtu/hr) and 202 MW (689 MBtu/hr) for road vehicles. The gas temperatures in the ceiling vary from 110°C (212°F) to 1365°C (2489°F).

It must be emphasized that most of the test results are dependent on the test conditions. These include low air velocities during most of the tests and a cross section significantly smaller than usually found in road tunnels. This overestimates the heat radiation coming back from the walls and may underestimate the amount of oxygen available in the tunnel.

The design fire size selected for design significantly affects the magnitude of the critical velocity needed to prevent backlayering. Table 13 provides general fire size data for a selection of road tunnel vehicles. It presents typical fire size data for passenger cars and multiple passenger cars, for buses, HGVs, and tankers; however, this does not allow for evaluation of

TABLE 13
TYPICAL FIRE SIZE DATA FOR ROAD VEHICLES

Cause of Fire	Peak Fire Heat Release Rate, 10^6 Btu/h (MW)
Passenger Car	17 to 34 (5 to 10)
Multiple Passenger Cars (2 to 4 vehicles)	34 to 68 (10 to 20)
Bus	68 to 102 (20 to 30)
Heavy Goods Truck	239 to 682 (70 to 200)
Tanker[3]	682 to 1,023 (200 to 300)

Source: NFPA Standard for Road Tunnels, Bridges, and Other Limited Access Highways (2008) (*19*).
Notes:
1. The designer should consider the rate of fire development (peak HRRs may be reached within 10 min), number of vehicles that could be involved in a fire, and the potential for a fire to spread from one vehicle to another.
2. Temperatures directly above a fire can be expected to be as high as 1800°F to 2550°F (1000°C to 1400°C).
3. Flammable and combustible liquids for tanker fire design could include adequate drainage to limit the area of pool fire and its duration (see Table 14).
4. HRR may be greater than listed if more than one vehicle is involved.

TABLE 14
EFFECT OF LEAKAGE DIAMETER AND DRAINAGE RATE ON THE FIRE SIZE OF FUEL TANKERS

Equivalent Diameter of Leakage [mm (in.)]	Leakage Mass Flow of Fuel [kg/s (lb/s)]	Calorific Power [MW (MBtu/hr)] Drainage Mass Flow of Fuel			
		0 kg/s (0 lb/s)	1 kg/s (2.2 lb/s)	2 kg/s (4.4 lb/s)	5 kg/s (11 lb/s)
15 (0.6)	0.5 (1.1 lb/s)	22 (75)	—	—	—
35 (1.4)	2.7 (6 lb/s)	120 (409.5)	76 (259)	33 (113)	—
50 (1.9)	5.6 (12.3 lb/s)	245 (836)	201 (686)	158 (539)	27 (92)

Source: PIARC (*21*).

multiple HGV or bus accidents. Fire HRR, especially for vans and heavy goods trucks, depend on the size of cargo load, which is usually unknown.

A risk analysis for the Oresund Tunnel (*43*) considers the possibility of fuel leakage from holes of 15, 35, and 50 mm (0.6, 1.4, and 1.9 in.) equivalent diameter. These represent the potential failure of small diameter fuel lines or a small amount of damage to a delivery hose flange. They do not represent the complete destruction of a delivery hose that would give a hole diameter of 100 mm (3.9 in.). The leakage flow depends on the diameter of the hole and the fluid pressure at the hole. For the holes considered, the mass flows are 0.5, 2.7, and 5.6 kg/s (1.1, 6, and 12.3 lb/s), respectively.

The drainage capacity of the drainage outlets is normally 10 times greater. However, it was assumed that in an accident this could obstruct and limit the amount of drainage. The calculations for the different fire scenarios gave calorific power outputs of between 22 MW (75 MBtu/hr) and 245 MW (836 MBtu/hr).

Fire duration can be determined by the amount of available combustible material. The amount of fuel is different for each study based on the type of vehicles, loads, and traffic patterns. Tables 15 and 16 present several examples on design fire scenarios in the Netherlands and France.

EXPLORING THE EMERGING ISSUES OF ALTERNATIVE FUEL VEHICLES ON DESIGN FIRES

Environmental issues such as climate change and scarcity of resources have stimulated the development of new energy carriers for vehicles. This also means that there will be an increase in the number of vehicles running on these new energy carriers in tunnels and other confined spaces. New energy carriers do not necessarily imply higher risks; however, they do represent a new situation with inherent new risks, and such risks need to be considered and evaluated. The mixture of different energy carriers, such as flammable liquids, gases lighter than air, gases denser than air, batteries, and so forth, can also constitute a risk itself, because there are situations where different safety measures need to be implemented depending on the energy carrier used and the scenario in question. Some countries have restrictions on the use of some energy carriers in confined spaces. This section explores the emerging issues of alternative fuel vehicles on design fires.

Natural Gas and Liquid Gas Vehicles

CNG and compressed biogas are primarily composed of methane, which is a gas lighter than air. Biogas can be classified as a renewable natural gas. CNG is the more widely used of the two. CNG is usually stored in a fuel tank at a pressure of 200 to 250 bar (2900 to 3625 psi). The use of CNG is increasing around the world and in 2008 there were more than 9 million CNG vehicles and 13,000 refueling stations worldwide.

The situation with a CNG engine is more complicated because the exhaust gas temperature from the CNG engine is much higher (~750°C or 1382°F) than from the diesel engine (~450°C or 842°F). Additional measures can be considered to reduce the risk of fire:

- Reduce the high exhaust temperature in the engine compartment by installing a water-cooled system. The exhaust system must be made of noncorrosive special steel with no leaks.
- Check the exhaust gas system for leaks and insulate as needed.
- Provide a means of ventilation (additional louvers) in the engine compartment for heat dissipation.
- Facilitate the removal of oil-contained contamination in the engine and gear compartments.
- Install fire alarm sensors on busses.

Hydrogen

Hydrogen is a colorless, odorless, tasteless, nontoxic, noncorrosive gas approximately 14 times lighter than air. Much research and development is currently focused on hydrogen and its feasibility as a vehicle fuel; however, in most cases only demonstration models are available (*46*). Hydrogen can be used either for internal combustion engine (ICE) vehicles or fuel cell vehicles (FCVs). It is expected that after 2015, fuel cells will be more common. There are several hydrogen vehicle projects currently being tested. There is a Network of Excellence called HySafe, which aims to safely introduce hydrogen technologies and applications. This network has

TABLE 15
DUTCH FIRE SCENARIOS FOR TUNNELS WITH LONGITUDINAL VENTILATION IN RELATION TO HEAT RELEASE RATES

Size	Heat Release Rate (MW) [MBtu/hr]	Scenario	Remarks
Small	6.1 [20.8]	- A passenger car is completely burnt - Estimated duration of the fire: 25 min - Smoke temperature less than 150°C (302°F) at a few meters from the source of the fire - Ventilation speed 1.5 m/s (295 fpm) - Jet fans will only be impaired if they are right above the fire - Fire fighting is possible from within a few meters of the source of the fire - Limited damage to the tunnel interior - Limited amount of soot	—
Medium	100 [341]	- A heavy goods vehicle loaded with wood is completely burnt - The temperature of the fumes is about 800°C (1472°F) at a distance of 50 m (164 ft) from the source - Ventilation speed 1.5 m/s (295 fpm) - Fire fighting is possible at a distance of 10 to 20 m (33 to 66 ft) from the source of the fire when protective clothing is worn - Damage to the tunnel interior, soot formation - Breakdown of jet fans at a distance of 150 to 300 m (492 to 984 ft) downstream of the fire is expected	Scenario applicable to Dutch tunnels in urban areas or on secondary roads where the transport of dangerous goods is forbidden
Large	300 [1,024]	- A tanker loaded with 50 m³ of gasoline is completely burnt - Estimated duration of the fire: 2 h - Fire fighting is possible at a distance of from 10 to 20 m (33 to 66 ft) from the source when the ventilation speed is increased to 3 m/s (591 fpm) and protective clothing is worn - Use of water/foam should be considered - The temperature of the smoke will be about 1400°C (2552°F) at a distance of about 20 m downstream of the fire - All jet fans will be damaged over a distance of 300 to 500 m (984 to 1,640 ft) downstream of the fire - Considerable damage to the interior of the tunnel over a large distance downstream of the fire; distance is increased when the ventilation speed is increased	Criterion for tunnels that are opened to the transport of dangerous goods (such as propane or other toxic substances)

Source: *Fire in Tunnels* (*9*).

TABLE 16
FRENCH DESIGN FIRES WITH COMPLEMENTARY DATA FOR CFD CALCULATIONS

	Clearance of the Tunnel			
Parameter	Height <2.7 m (8.9 ft)	Height 2.7 m to 3.5 m (8.9 ft to 11.5 ft)	Height >3.5 m (11.5 ft) (no dangerous goods allowed)	Height >3.5 m (11.5 ft) (dangerous goods allowed)
Typical Fire	2–3 cars	1 van	1 HGV	1 fuel tanker
Heat Release Rate (MW) [MBtu/hr]	8 [27]	15 [51]	30 [102]	200 [682]
Smoke Flow Rate (m^3/s) [ft^3/s]	30 [1,059]	50 [1,766]	80 [2,825]	300[1] [10,594]
Growth Time t_g (min)	5	5	10	10
Peak Duration t_{max} (min)	20	30	60	60
Decline Time t_d (min)	20	20	30	30
Released Energy (GJ) [MBtu]	15 [14.2]	40 [37.9]	150 [142.1]	1000 [947.2]

Source: *Fire in Tunnels* (*9*).
[1]In France, this smoke flow rate is generally not taken into account for the design of semi-transverse ventilation, even if the transport of dangerous goods is allowed.

led to a number of projects, including HyTunnel and InsHyde. The goal of HyTunnel is to develop codes, standards, and regulations so that additional risks from the introduction of hydrogen vehicles into tunnels can be handled safely. During the test period, no major safety-related incidents occurred to the fuel cell buses. However, for the ICE buses there was one unexpected release of hydrogen when a check valve within the tank nozzle failed.

The results indicated that owing to the nature of flame and fire development, tunnels with greater slopes and with horseshoe cross sections (compared with equivalent rectangular cross sections) present lower hazards. In InsHyde, many different aspects of hydrogen safety in confined spaces are evaluated and discussed, such as regulations, detection, ventilation, fire, and explosion. Both computer modeling and experiments were performed to study different parameters and effects. In that study, it was determined that among hydrogen incidents the ignition source could not be identified in 86% of the cases and was probably caused by spontaneous ignition. However, in another research project, Wu (*47*) showed that conditions of oxygen deficit could be reached for a higher release rate of hydrogen. This can lead to higher temperature ceiling flows and damage to tunnel structures. For hydrogen buses with internal combustion engines, these impacts also apply, and the installation of hydrogen sensors is advisable.

Batteries

Electric cars that use batteries as an energy source are seen as the single most promising future energy carrier, in particular, for city traffic. One problem is the relatively short available driving distance before recharging is needed. Therefore, hybrid solutions are currently of greatest interest. In most cases a hybrid vehicle has both a conventional internal combustion engine and an electric motor. There are also plug-in electric vehicles, with batteries that can be plugged in for charging, such as to house electricity, in addition to being charged while running.

Presently, nickel-metal-hydride batteries are the most common used batteries in hybrid vehicles. These batteries are robust, but have a relatively high self-discharge rate. Therefore, for a variety of reasons, most interest is currently directed to lithium-ion batteries. Lithium-ion batteries have a high energy density and a high cell voltage. In addition, the maintenance need is low and there are no memory effects. However, to limit the peak voltage during charging for safe operation, a protection circuit is built into each battery pack. This also limits the discharge current. Other safety features are also studied for lithium-ion batteries.

Two main types of risks can occur with vehicle batteries. One is that the battery (system) itself is the cause of the incident, such as with an electrical fault, which can be caused by a short circuit or an overcharge, and could result in a fire. The other is that the battery is exposed to an external risk, either some mechanical force or a thermal attack, as with a fire. There have been instances of batteries exploding or releasing jet fires. There are some who believe that electric cars have been responsible for the larger number of fires when compared with nonelectric cars. This type of fire can also emit toxic fumes from hydrogen fluoride and oxides of carbon, aluminum, lithium, copper, and cobalt. The lithium salts used in the electrolyte contain fluorine or a chlorine compound, where hydrogen fluoride or hydrogen chloride can be produced during a fire.

There are some restrictions and regulations concerning the use of alternative energy carriers, especially for compressed or liquefied gases. In relation to underground constructions, most restrictions concern underground garages; however, some also specifically address tunnels. Many of the restrictions can be related to LPG, which is also considered to be an alternative fuel, together with liquefied natural gas (LNG), CNG, hydrogen, propane, methanol, ethanol, and biodiesel, in accordance with the U.S. Energy Policy Act of 2005. LPG vehicles run on liquefied gas, which is denser than air.

The following are examples of tunnels where LPG and CNG are restricted (see Table 17):

- In Maryland, LPG is forbidden in the Baltimore Harbor and Fort McHenry tunnels.
- LPG is forbidden in the Summer, Callahan, Prudential, and Dewey Square tunnels in Massachusetts.
- LPG is forbidden in the Holland, Lincoln, Brooklyn Battery, and Queens Midtown tunnels in New York and New Jersey.
- In Virginia, an LPG ban covers the Chesapeake Bay Bridge tunnel.
- In Italy, vehicles using LPG or gas are labeled before entering the Mont Blanc Tunnel or the Frejus Tunnel.
- In France and the United Kingdom vehicles running on gas are prohibited in the Euro Tunnel.
- In Austria, LPG and CNG are not permitted in the Tauern Tunnel.

However, there are no restrictions on LPG vehicles in tunnels in Japan and many other countries.

Some examples of LPG fire incidents include:

- A car crash in a highway tunnel near Palermo, Italy, occurred on March 18, 1996. The accident involved a tank truck transporting LPG, which caused propane to be released, which formed a burning gas cloud resulting in critical burns to 25 people. The subsequent boiling liquid expanding vapor explosion (BLEVE) led to five fatalities. The cause of the accident was not strictly the result of a new energy carrier, but it did involve a vehicle transporting fuel for a new energy carrier.

TABLE 17
SUMMARY OF KNOWN INCIDENTS INVOLVING CARS RUNNING ON LPG OR NEW ENERGY CARRIERS (NOT ALL IN TUNNELS)

Date	Place	Type of Premises	No. of vehicles	Fuel	Ignition	Consequences
Jan. 31, 1999	Venissieux, France		1	LPG	Arson	Explosion; 6 fire fighters severely injured
Sep. 2002	U.S.		1	CNG	Car fire	Rupture of gas cylinder
Nov. 9, 2002	Seine-et-Marne, France	Garage	1	LPG	Unknown	Explosion; building of origin collapsed; in total 39 buildings affected
Aug. 28, 2005	Firenze, Italy	San Donato tunnel		LPG	Engine fire	Dense smoke
June 2006	Collatino, Italy	Parked on the street	1	LPG	Arson	Explosion, several cars, 2 garages, shops, fire spread to apartments
March 2007	Seattle, WA U.S.	Row of parked vehicles	12	One with CNG	Arson	12 cars damaged or destroyed; CNG tank exploded when fire fighters were approaching; debris approx. 30 m away
May 2007	Carson, CA, U.S.	Refueling	1	CNG		Driver killed
Dec. 16, 2007	Salerno, Italy	Underground garage		LPG	Leakage of gas from vehicle	Explosion; one 3-storey building totally destroyed; 5 other buildings affected
June 7, 2008	U.S.	Running on the highway	1	Hybrid converted to plug-in	Short circuit	One burned-out car
Sept. 19, 2008	Rovigno, Italy	Underground garage		LPG		Fire spread to neighboring garage and threatened the building
Oct. 2008	South Yorkshire, U.K.	Running on the road	1	LPG	Lighting of cigarette	Explosion, burns, broken windows
Nov. 8, 2008	Mallaca, Malaysia	Filling station	1	LPG		Explosion of vehicle; passengers severely injured
Dec. 28, 2008	Sampford Peverell, U.K.	Running on the highway	1	LPG	Unknown	One burned-out car
Oct. 28, 2009	Marigliano, Italy	Parking	6	One with LPG	The cause of the initial fire unknown	Large explosion damaged vehicles and buildings

Source: Lönnermark (*48*).

- On the night of January 31, 1999, a vehicle fuelled with LPG was set on fire by an arsonist in Vennissieux outside Lyon, France. The LPG system was not equipped with a safety valve. This led to an increase in pressure in the tank during the fire and the tank later exploded. Six firemen attempting to extinguish the fire were severely injured. This incident led to action that could help avoid this kind of incident in the future. Later, a requirement that such vehicles have safety valves was introduced.
- On November 9, 2002, a vehicle fuelled with LPG began to leak in a garage in Seineet-Marne in France. The high density of the gas allowed it to spread over a large area and down into the basement. At 11 p.m. the gas ignited, an explosion occurred, and the building collapsed, burying several individuals, who were later saved. In total, the explosion affected 39 buildings within a radius of 200 m. The roof of the LPG vehicle was found 150 m from the place where the vehicle had been parked.
- In June 2006, arsonists ignited an LPG-fuelled vehicle in Collatino, Italy. The car was parked with other vehicles on a street outside an apartment building. The fire started in the rear part of the vehicle, where the LPG tank was positioned. The subsequent explosion of the tank led to an intense fire, which ignited several other cars. The pressure wave destroyed two small garages and shops located in the apartment building. The fire damaged the façade and several balconies.
- In March 2007, an arsonist set fire to a row of vehicles parked under a highway bridge in Seattle. The first responders were not aware that one of the cars was CNG-fuelled. When they were 15 to 20 m (49.2 to 65.6 ft) from the burning vehicles the CNG tank exploded. The fuel tank and other large pieces of debris landed about 30 m (98.4 ft) from the CNG vehicle. The fuel tank was equipped with a safety valve, but exploded before the valve could release the pressure.
- In May 2007, a CNG tank in a vehicle in Carson, California, ruptured. The rupture occurred during refueling and killed the driver. A day earlier, the driver had collected the vehicle from a repair shop after a collision three weeks prior.
- In June 2008, a fire in a hybrid car converted to a plug-in started while the car was running. The car used a lithium-ion battery, which was partly damaged during the fire, but still provided power. According to the investigation, the most probable explanation of the incident was incorrect electrical wiring, which led to excessive heat generation. The heat destroyed some cells in the battery leading to a short circuit and the fire.
- In October 2008, a car running on LPG suddenly exploded in South Yorkshire, United Kingdom. Remarkably the driver survived and was able to describe the accident. He had recently refueled this car and was proceeding slowly when he smelled gas. He had been told that this was normal after refueling. When he lit a cigarette the gas was ignited and filled the car with flames. Owing to the increase in pressure, the windows broke and the bonnet and the trunk blew opened. The driver suffered minor burns to the face and body, but the seat absorbed most of the energy of the explosion, saving his life. The most likely explanation for the explosion was a leak in the tube between the filling valve and the tank. The car, which had been purchased second-hand three weeks earlier, had been checked and approved twice at workshops.
- The most recent reported incident occurred on October 28, 2009, in Marigliano, Italy. A fire started in a parked car running on a traditional fuel. It developed quickly and spread to nearby vehicles. Six cars were ultimately involved, including one using LPG, which quickly exploded after catching on fire. The explosion damaged cars in the vicinity and a nearby building. Debris from the exploded car was found on the balcony of that building and windows were broken up to the eighth floor. Stores at street level sustained severe damage.

In addition to these car fires, some conclusions can be drawn from various bus fires. Three bus fires involving CNG tanks are analyzed here. The first responders were unable to extinguish these fires. The first conclusion was that the pressure relief devices (PRDs) do not always release. This can happen when there is local thermal exposure, such as from an impinging jet flame, which leads to insufficient heat for the PRD, or it could be a malfunctioning heat release device. Either way it is important to minimize or eliminate areas with weaker fire protection, such as sun roofs, which could lead to such localized fire exposure. Another important issue is the time necessary to completely empty the tank. In the incidents described, it would be preferable to have early PRD opening and fast emptying of the tank, although the situation could be completely different if the buses had been located in a confined environment such as a tunnel or underground garage. One main conclusion is that the safety of these types of vehicles does not rely only on component tests. For example, it is important to test the entire system, where the tanks and other components can be evaluated using relevant and realistic scenarios.

The incidents summarized and described earlier are not meant to imply that all vehicles running on new energy carriers will explode when used or when exposed to fire. However, seeking the worst case scenarios is important when new energy carriers are developed. It is also important to realize that all risks are not eliminated by introducing PRDs. The outcome still depends on the design of these devices and on the fire scenario.

Wu of Sheffield University performed a CFD analysis of hydrogen fires in tunnels. Hydrogen cars generate fast, high rising flames that quickly reach high temperatures (*47*). The body of the hydrogen car was not ignited and the flames lasted only a few minutes. It was concluded that a supercritical velocity in the tunnel can completely eliminate the smoke backlayering with a normal hydrogen HRR or keep the backlayering under control with a high HRR. She concluded that with a high HRR the flame inside the tunnel may have encountered oxygen deficiency. This will result in the impingement of hydrogen jet flames on the tunnel ceiling, which would produce high temperature ceiling flows reaching substantial distances and damage the tunnel infrastructure. The oxygen-deficient hydrogen fire also poses a risk of flashover inside the tunnel and ventilation ducts.

In early 2004, fire tests of FCVs in the event of low pressures of 20 MPa (2900.8 psi) and high pressures of 35 MPa (5076.3 psi) were conducted in Japan in a simulated full-scale tunnel 80 m (262.5 ft) long with a cross-sectional area of 78 m^2 (840 ft^2). Tests were also performed with the natural gas cars (CNG) for comparison. CNG cars and FCVs generated a large quantity of heat compared with gasoline cars. The flame of the CNG cars and FCVs tended to rise faster when compared with gasoline cars. The highest air temperature was reached at 6 m (19.7 ft) above the roadbed at 319°C (606°F) for CNG cars, 243°C (469°F) for FCVs with high pressure, 228°C (442°F) for gasoline cars, and 166°C (331°F) for FCVs with low pressure. The maximum radiation heat for CNG cars was 5125 W/m^2 (1625 Btu/hr/ft^2); for gasoline cars, 4471 W/m^2 (1417 Btu/hr/ft^2); for FCVs with high pressure, 4141 W/m^2 (1313 Btu/hr/ft^2); and for FCVs with low pressure, 1774 W/m^2 (562 Btu/hr/ft^2). In all cases, the temperature rose to 1100°C (2012°F). In the case of FCVs with high pressure the temperature grew rapidly to 1435°C (2615°F) within 290 s. According to an inspection of the concrete above the fire, damage was limited, with little impact on its compression strength. At its conclusion, the CNG and FCV cars caught fire rapidly and burned intensely. With air velocities of 2 m/s (394 fpm), stratification was observed; therefore, the tenable environment was maintained at 1.5 m (4.9 ft) from the roadbed. A concern was raised of possible gas detonation if tunnel air velocity reached close to 0. Additional research and modeling is needed.

It is difficult to properly evaluate what are the emerging trends concerning use and what risk scenarios are possible or most likely with alternative fuel vehicles. This can be, for example, a problem for the rescue services, because they will be exposed to incidents involving different types of fuels and energy carriers. This means that they must have information concerning not only the situation itself but also the energy carriers involved. Some tunnels require drivers of vehicles running on CNG or LPG to report this before entering the tunnel and to correspondingly label their vehicles. It is important that an overall system be developed as the diversity of vehicles increases.

There are a variety of views on how vehicles running on LPG, CNG, or similar fuels are treated and what safety measures are needed. It is important that restrictions are premised on correct information based on additional systematic research on new energy carriers. It is important to provide correct and detailed information concerning safety issues and the behavior of these energy carriers where a fire can develop.

Systems, not only components, need to be tested to within different scenarios and that models be developed for these scenarios. When the scenarios are described in a representative way, technical safety solutions, mitigations systems, and rescue service tactics can be developed. It is also important to study how the different systems (detection, ventilation, and mitigation) interact, and how the models developed are altered depending on the scenario.

The incidents analyzed show that when there is a fire new energy carriers can explode with catastrophic consequences. The outcome does, however, vary with different scenarios. It is important to learn from incidents that have occurred, and that experiments and relevant research be performed to maximize the understanding of the risks. Such incidents also show that safety systems do malfunction, especially in used vehicles. Such malfunctions can be the result of accidents, mistakes, conversions, or erroneous repairs, but the consequences of such malfunctions are always potentially serious.

The field of new energy carriers is very diverse and constitutes many different areas of research. This makes a detailed review of all aspects of risks associated with new energy carriers and safety in tunnels beyond the scope of this study. On the other hand, this is exactly why this issue is so important. When new energy carriers are developed and used in vehicles traveling through tunnels, a variety of different safety aspects converge and need to be dealt with properly and promptly. Clearly, more research is needed concerning how safety in tunnels is affected by the introduction and development of new energy carriers.

FIRE SMOKE AND SMOKE PRODUCTION—LITERATURE REVIEW

Almost all fires generate smoke. Smoke is a mixture of gases, fumes, and particles. The generation of smoke is affected by the following factors:

- Possible reduced supply of oxygen to the fire site,
- Heat release,
- Heat convection,
- Longitudinal slope,
- Type of ventilation,
- Dimensions of the traffic space and possible obstructions,
- Thrust caused by any moving vehicles, and
- Meteorological influences (wind strength and direction).

Smoke mixes with the surrounding air and dilutes in the plume. This process depends on the size of the source of fire, fire and air temperature, buoyancy, and height in the plume. With no obstructions and no longitudinal air movement, the plume of smoke and hot gases rises to the tunnel ceiling directly above the source of the fire and spreads in both directions, fire forming a relatively dense smoke layer. A relatively low-density cold smoke layer sits below the hot layer.

Basically, it can be said that as a result of the heat released around the fire site and thermal buoyancy, the smoke is lifted up to the ceiling near the fire site and spread in the upper area of the tunnel. The smoke continues its flow in one direction when the longitudinal velocity is high (with or without backlayering), but in both directions when the longitudinal velocity is low. Thus, there is a limited space above the road surface without any smoke gases, at least for a short period of time. Note that this may not be true for small fires with limited heat dissipation, because the smoke can be relatively cold.

A smoke layer may be created in tunnels at the early stages of a fire with essentially no longitudinal ventilation. However, the smoke layer will gradually descend further from the fire. If the tunnel is very long, the smoke layer may descend to the tunnel surface at a specific distance from the fire depending on the fire size, tunnel type, and the perimeter and height of the tunnel cross section. When the longitudinal ventilation is gradually increased, the stratified layer will gradually dissolve. A backlayering of smoke is created on the upstream side of the fire. Downstream from the fire there is a degree of stratification of the smoke that is governed by the heat losses to the surrounding walls and by the turbulent mixing between the buoyant smoke layers and the normally opposite moving cold layer. The particular dimensionless group, which determines whether a gas will stratify above another, is the Richardson number (Ri) defined by Eq. 16. The Richardson number is similar to the inverse of the Froude number (Fr) defined by Eq. 15; however, the Richardson number is thought of as controlling a mass transfer between layers, whereas the Froude number gives the general shape of a layer in an air stream.

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 phenomenon is 3D in the region close to the fire plume. The gravitational forces tend to suppress the turbulent mixing between the two different density flows.

It becomes possible for cold unreacted air to bypass or pass beneath the fire plume without mixing, even though the flow is turbulent. The longitudinal aspect of the fuel involved in the fire, therefore, may play an important role in the mixing process between the longitudinal flow and the fuel vapors generated by the fire.

There is a correlation between temperature stratification at a given location and the local mass concentration of chemical compounds. There is also a correlation between local smoke OD (or visibility), the local density (or temperature), and the oxygen concentration in tunnels. Therefore, it is reasonable to assume that there is a correlation between the local temperature stratification, the gaseous composition (CO, CO_2, O_2, etc.), and smoke stratification in tunnels. The temperature stratification is, however, not only related to the air velocity but also to the HRR and the height of the tunnel. These parameters can actually be related through the local Froude number (Fr) or Richardson number.

Three distinct regions of temperature stratification are defined by the Froude number (Fr) or Richardson number. 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. Also, this region is next to the fire location and allows for the evacuation of motorists.

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 II1), when $Fr > 10$, has insignificant vertical temperature gradients and consequently insignificant stratification.

Because a tunnel can be used by different types of vehicles, such as cars, buses, trucks, and special vehicles, which may have different loads (persons, nonflammable cargo, flammable cargo, explosives, toxic goods, etc.), it is possible that tunnel fires may differ in terms of quantity and quality. In most cases, car fires are relatively harmless for small tunnel fires with minor temperature and smoke development. However, it is very dangerous when there is a tanker fire with the resulting high temperatures and enormous smoke production, plus the danger of explosion. Therefore, it is not possible to describe the temperature and smoke development for every possible kind of tunnel fire.

The main design parameter is the smoke flow rate produced by the fire. For the smoke flow rates by fires of passenger cars, buses, and trucks, the PIARC assumptions in the Brussels' report were confirmed by the EUREKA fire tests. German regulations (RABT from the year 1994) quote smoke production rates somewhat higher than those of PIARC.

CFD calculations made in France by CETU (Centre d'Etudes des Tunnels) show a decrease in smoke volume flow with increased distance to the fire for HRRs above 60 MW (205 MBtu/hr) (*49*), as shown in Figure 14.

For fires up to 60 MW (205 MBtu/hr), the volume flow does not depend on this distance. From at least 10 to 120 m (32.8 to 393.7 ft) from the fire, the smoke cools down; how-

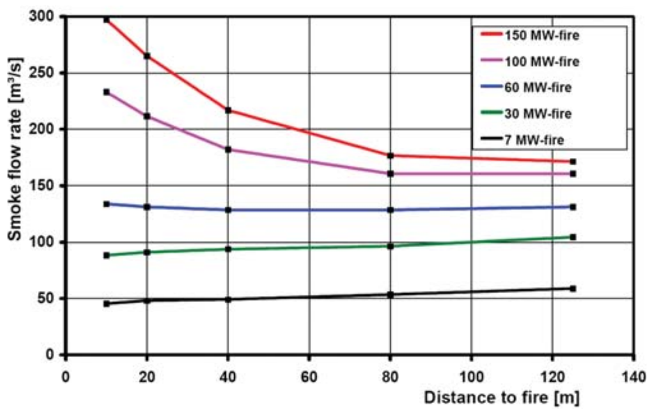

FIGURE 14 Variation of smoke volume flow with (plume flow) distance to fire (CETU)(*9*).

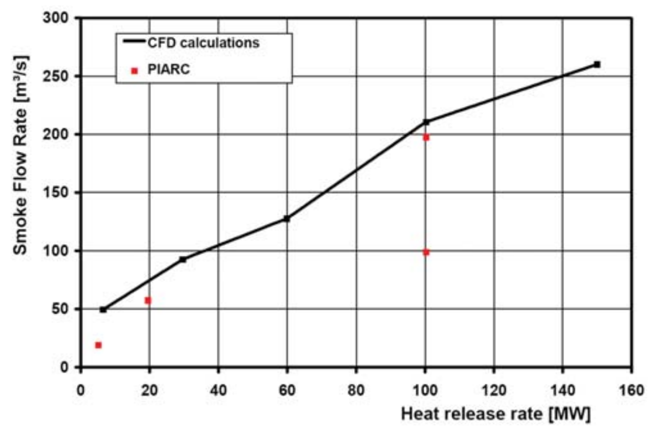

FIGURE 15 Smoke flow rate versus fire heat release rate (*9, 50*).

ever, fresh air is entrained so that the volume flow does not change. For 100–150 MW (341–512 MBtu/hr) fires, the entrainment of fresh air does not compensate for the very strong reduction of smoke temperature 50 to 100 m (164 to 328 ft) from the fire.

These calculations were performed with no longitudinal ventilation airflow. The smoke flow rate was calculated as the volume flow of gases that moved away from the fire in the upper part of two cross sections located at given distances at both sides of the fire.

Also, according to the CFD results, the smoke flow rate varies nearly linearly with the HRR—from about 50 m^3/s (1,765.7 ft^3/s) at approximately 10 MW (34 MBtu/hr) to about 250 m^3/s (8,828.7 ft^3/s) at approximately 150 MW (512 MBtu/hr), as shown in Figure 15.

Table 18 presents smoke production rates, CO, and CO_2 as published in different literature sources (summarized experimental results and standards values). To convert the smoke masses produced to smoke volumes it is necessary to know the smoke temperatures. The theoretical stoichiometric combustion temperatures of regular gasoline are about 2000°C (3632°F). The real fire temperatures are usually much lower, primarily because the combustion is not stoichiometric or because the smoke mixes with air.

The dangerous nature of smoke gases in tunnel facilities not only results from the visibility obscuring effect but also from

TABLE 18
SMOKE, CO_2 AND CO PRODUCTION

Burning Vehicle	Smoke Flow [m^3/s (ft^3/s)]				CO_2 Production (EUREKA tests) [kg/s (lb/s)]	CO Production [kg/s (lb/s)]
	PIARC (1987)	RABT (1994)	EUREKA Tests	CETU (1996)		
Passenger Car	20 (706)	20–40 (706–1,412)	—	20 (706)	—	—
Passenger Van (plastic)	—		30 (1,059.4)	30 (1,060)	0.4–0.9 (0.88–2)	0.020–0.046 (0.04–0.1)
2–3 Passenger Cars	—		—	30 (1,060)	—	—
1 van	—		—	50 (1,765)	—	—
Bus/Truck Without Dangerous Goods	60 (2,120)	60–90 (2,120–3,180)	50–60 (1,765–2,120)	80 (2,825)	1.5–2.5 (3.3–5.5)	0.077–0.128 (0.17–0.28)
Heavy Goods Vehicle	—		—	50–80 (1,765–2,825)	6.0–14.0 (13.2–30.9)	0.306–0.714 (0.67–1.57)
Gasoline Tanker	100–200 (3,531–7,063)	150–300 (5,300–10,600)	—	300 (10,600)	—	—

Sources: *Fire in Tunnels* (*9*) and PIARC (*21*).

the possible toxicity of gases including CO, carbon dioxide (CO_2), and other gases depending on the burning materials, especially toxicity caused by cargo. To address these concerns, during the EUREKA and Runehamar fire tests, the CO and CO_2 levels were monitored at several measuring points along the tunnel.

During the EUREKA fire tests, the CO level was monitored at several measuring points along the tunnel. In the region from approximately 20 to 30 m (65.6 to 98.4 ft) downstream of the burning vehicles, the following peak CO concentrations were measured at head height:

- Passenger van (plastic): 300 ppm
- Public bus: 2,900 ppm
- HGV: 6,500 ppm.

CO concentrations of more than 500 ppm were exceeded from about 10 to 15 min from the start of the fire and lasted approximately 2 h during the bus fire and approximately 15 min during the HGV fire. During an experiment with a mixed fire load, CO concentrations of 500 ppm and more occurred not before about 80 min after the start of the fire and lasted for 90 min.

The EUREKA results depend very much on the different ventilations of the test tunnel during the fire tests. Furthermore, they are related to the type of burning material. Therefore, the EUREKA results may not be transferred directly to other tunnels. However, the EUREKA results indicated that downstream of the fires there is, at least for larger fires, a need for escape and rescue within about 10 to 15 min from the start of a fire. Harmful CO concentrations are also expected in the progressive stage of vehicle fires. The mass generation of CO_2 can be estimated using a ratio of 0.1 kg/s per MW of HRR.

A reasonable linear correlation between the production rates of CO_2 and CO was found when analyzing the EUREKA test data. These results suggest an average ratio of 0.051, with a standard deviation of ±0.015. This average is used for the calculation of the CO production rates. As an order of magnitude, the volume concentration of CO is also approximately 5% of the concentration of CO_2.

The correlation of the smoke-dependent visibility measured by the OD and the concentration of CO_2 produces a linear relation when a correction for the smoke gas temperature is made. The following formula can be used to estimate the OD from the CO_2 volume concentration:

$$OD = \alpha \; \left(T_0 / T\right) \; \left[CO_2\right] \tag{18}$$

where:

T is the local temperature in Kelvin, $T_0 = 273$ K;
$[CO_2]$ is the concentration in percent of volume; and
α is a coefficient which is:

- Approximately 1.3 for the plastic passenger van fire,
- Approximately 0.5 for the bus fire, and
- Approximately 0.8 for the HGV fire.

Another approach is based on the mass OD. Visibility depends on:

- Smoke density,
- Tunnel lighting,
- Shape and color of objects and signs,
- Light absorption of smoke, and
- Toxicity of smoke (eyes irritating).

The visibility in smoke can be related to the extinction coefficient, K, by the following equation:

$$K = \frac{OD}{X} \ln\left(10\right) \tag{19}$$

where:

OD is the optical density, and
X is the path length of light through smoke.

The optical density per unit optical path length can also be expressed as:

$$\frac{OD}{X} = \zeta \;\; Y_s \;\; m_f \big/ V_T = D_{\text{mass}} \frac{Q}{uAH} \tag{20}$$

where:

ζ is the specific extinction coefficient of smoke or particle OD (m^2/kg);
Y_s is the yield of smoke (g/g);
m_f denotes the mass flow of material vapors of the burning material;
V_T is the total local volumetric flow rate of the mixture of fire products at the actual location (measuring point) and air (m^3/s);
$\zeta\ Y_s$ is defined as mass OD, D_{mass} (m^2/g);
Q is the HRR in kW at the actual location and H is the effective heat of combustion (kJ/kg) obtained from the tables for different materials (but not of the burning vehicle); and
u (m/s) is a unified longitudinal ventilation velocity across the tunnel cross section A (m^2).

For objects such as walls, floors, and doors in an underground arcade or long corridor the relation between visibility and the extinction coefficient was defined earlier by Eq. 13.

Thus, by combining the equations, a correlation between the visibility V and the HRR in a tunnel at an actual position

TABLE 19
MASS OPTICAL DENSITY FROM BURNING VEHICLES

Type of Vehicle	Average Mass Optical Density D_{mass} (m^2/kg or ft^2/lb)
Car (steel)	381 (1,860)
Car (plastic)	330 (1,610)
Bus	203 (991)
Truck	76–102 (371–498)

Source: *Fire in Tunnels* (*9*).

downstream of the fire with a ventilation air velocity of *u* (m/s) is:

$$V = 0.87\frac{uAH}{QD_{mass}} \qquad (21)$$

In Table 19 values of D_{mass} for different types of vehicles are given based on large-scale tests. These values may be used as an engineering tool for determining the visibility in fires depending on the fuel load.

For CFD modeling, engineers use equations and tables of yields of CO, CO_2, HCN, heat of combustion, production of soot, and mass OD for different types of materials, such as wood, polyurethane foam, polystyrene, and mineral oil. Such tables can be found in the *SFPE Handbook for Fire Protection Engineering* (*51*) and other literature. Surprisingly, the vehicles are assumed to be one material, which leads to inconsistency in the results, as there is no uniform agreement on the numbers to use and to the inaccuracy of the CFD results.

The average mole fraction $X_{i,avg}$ of CO_2, CO, or HCN over the cross section of the tunnel and at a certain position downstream of the fire can be obtained from the following general equation:

$$X_{i,avg} = Y_i \times M_a / M_i \times Q(T) / m_a \times H_T \qquad (22)$$

Assuming $m_a \sim m_g$, where m_g is the mass flow rate of combustion gases. Here M_a is the molecular weight of air, M_i is the molecular weight of chemical species *i*, and Y_i is the mass yield of species *i* for well-ventilated fires. The value of $X_{i,avg}$ can be converted into a percentage by multiplying it by 100. The yields of Y_{CO_2}, Y_{CO}, and Y_{HCN} for well-ventilated conditions can be obtained for different fuels.

Table 20 presents some values for different fuels for well-ventilated conditions. A lack of sufficient experimental data and test results requires designers to use values from this table. By using this table, the designer is making an assumption by replacing an actual vehicle fire with pseudo-fuel. Different designers use different fuels and different values to approximate the actual fuel, which causes inconsistency in modeling and design results.

The yield values are the mean values for different material types (polyurethane foam, polystyrene, mineral oil). However, there is a need to replace the simulated materials with design values for fires involving HGVs, buses, cars, and tankers. Additional testing results are needed.

TEMPERATURE OF FIRE GASES AND TUNNEL WALLS

Tunnel fires significantly increase the air temperature in the tunnel roadway and in the exhaust air duct. Therefore, both the tunnel structure and ventilation equipment are exposed to high smoke and gas temperature. The air temperatures,

TABLE 20
YIELDS OF CO_2, CO, HCN, AND SMOKE AND EFFECTIVE HEAT OF COMBUSTION, FOR WELL-VENTILATED FIRES

Type of Material	Y_{CO_2} kg/kg	Y_{CO} kg/kg	Y_{HCN} kg/kg	Y_s kg/kg	D_{mass} m^2/kg (ft^2/lb)	H_{ec} MJ/kg (Btu/lb)
Wood	1.27	0.004		0.015	37 (181)	12.4 (5,331)
Rigid Polyurethane Foam	1.50	0.027	0.01	0.131	304 (1,480)	16.4 (7,050)
Polystyrene	2.33	0.06		0.164	335 (1,640)	27 (11,610)
Mineral Oil	2.37	0.041		0.097		31.7 (13,630)
Swiss Fire Modeling Assumption on Average of Three Materials Above	2.07	0.043	0.01	0.13		

Source: *SFPE Handbook of Fire Protection Engineering* (*51*).
Y_s = yield of smoke.
D_{mass} = mass optical density and is proportional to yield of smoke.
$H_{ec} = XH_T$ – effective heat of combustion.
Mass loss rate of the fuel, kg/s:

$m_f = Q(T)/ H_{ec}$.

$Q(T)$ = fire heat release rate, HRR (kW).

TABLE 21
MAXIMUM AIR TEMPERATURES EXPERIENCED AT VENTILATION FANS DURING MEMORIAL TUNNEL FIRE VENTILATION TEST PROGRAM

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)

Source: *ASHRAE Handbook* (*22*).
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.

shown in Table 21, provide guidance in selecting design exposure temperatures for ventilation equipment.

British standards provided data on distances over which jet fans were assumed to be destroyed by the fire; this is reproduced in Table 22. BD 78/99 also specifies that heavy items, such as fans, subjected to temperatures of 450°C (842°F), are to be designed to not fall down during the firefighting phase (*52*).

The French Inter-Ministry Circular (2000) specifies that jet fans must be capable of operating continuously in smoke-laden air at a temperature of 200°C (392°F) for at least 2 h. For transverse ventilation systems, a distinction must be made on the basis of whether the fans are or are not likely to be subjected to very high temperatures. In the general case, extraction fans, located at the end of a duct, must be capable of operating at a temperature of 200°C (392°F) for at least 120 min. However, under certain circumstances, it may be necessary for the fans to be capable of withstanding 400°C (752°F) for at least 120 min. Rather than providing information on the distances over which jet fans may be considered as destroyed, the French guidance provides smoke temperatures at various distances (CETU 2003). This is reproduced in Table 23. This also refers to the need to ensure that equipment does not fall when exposed to a temperature of 450°C (842°F) for at least 120 min.

Different fire characteristics are needed depending on whether the purpose is to design the tunnel structure or the ventilation facilities.

- The design of structures for fire resistance is based on the temperature of the hot air (degrees centigrade or degrees Fahrenheit) and radiation heat versus time.
- The design of a ventilation system is based on the HRR (thermal power in megawatts or million British thermal units per hour) or the smoke release rate (flow at the temperature of the hot smoke in cubic meters per second) versus time.

The dependence on time is important for evaluating the conditions at the beginning of the fire, taking into account the self-rescue phase (time for the fire department to arrive and get organized).

PIARC recommends the following maximum temperatures at the tunnel wall or ceiling to be considered for

TABLE 22
DISTANCES OVER WHICH JET FANS ARE ASSUMED TO BE DESTROYED BY FIRE (BD 78/99)

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)

Source: Hall (*52*).

TABLE 23
SMOKE TEMPERATURES NEAR THE CEILING, WITH AIRFLOW CLOSE TO CRITICAL VELOCITY

Downstream Distance	10 m	100 m	200 m	400 m
Light Vehicle	250°C	80°C	40°C	30°C
Heavy Vehicle	700°C	250°C	120°C	60°C
Tanker	>1000°C	400°C	200°C	100°C

Source: Hall (*52*).

tunnel structure and the cargo-traffic regulations for specific tunnels:

- Passenger car—400°C (752°F)*
- Bus/small truck—700°C (1292°F)*
- HGV with burning goods (not gasoline or other dangerous goods)—1000°C (1832°F)
- Gasoline tanker (general case)—1200°C (2192°F)
- Gasoline tanker (extreme cases: e.g., no benefits owing to tunnel drainage and limited leakage rate; large tanker; avoidance of the flooding of an immersed tunnel)—1400°C (2552°F).

These temperatures were estimated for a location 10 m (32.8 ft) downwind of the fire near the tunnel walls at the minimum air velocity to prevent backlayering. The EUREKA tests confirmed these maximum temperatures. The tests themselves gave slightly higher results for the passenger cars [up to 500°C (932°F), depending on type] and the coach [800°C (1472°F)] because of the small cross-sectional area and the low air velocity used [0.3 m/s and 0.5 m/s (59.1 and 98.4 fpm)] in the test tunnel. The fire tests of EUREKA and Runehamar also showed that fires resulting from HGVs can produce maximum temperatures between 1000°C and 1350°C (1832°F and 2462°F) at the tunnel ceiling. For fully developed fires of gasoline tankers, temperatures between 1200°C and 1400°C (2192°F and 2552°F) are studied.

As can be seen by Figure 16 in the EUREKA tests, temperatures of more than 300°C (572°F), which can be dangerous to the steel reinforcement of the concrete tunnel lining, were found as far as approximately 100 m (328 ft) downstream of the fire. In addition, because of backlayering, this temperature can be reached about 30 m (98.4 ft) upstream of the fire. According to actual fires and to the Memorial Tunnel tests, the extension of this region can be quite different from these values owning to many factors, such as the ventilation, tunnel grade, surface roughness, and fire-resistant coatings.

Many known real tunnel fires and also the EUREKA and Runehamar fires showed a very fast development during the first 5 to 10 (sometimes 15) min. The gradient of temperature is especially steep at the beginning of a full car fire, with a corresponding high emission of heat and smoke. Between 7 and 10 min after ignition a flashover needs to be taken into account (even sooner in the case of a passenger car).

The temperature during the Runehamar fires followed the Rijkswaterstaat (RWS) curve. That test comprises the largest amount of combustible material of the four tests conducted.

With the lowest calorific energy output the temperatures were recorded to be in the same magnitude, although for a shorter period of time. The duration of the hot phases of the EUREKA and Runehamar fires covered normally a time interval of about 30 min after the ignition stage. On the other hand, the Mont Blanc and Nihonzaka fires lasted significantly longer. The EUREKA and Runehamar tests showed a steep decline of temperatures just after the hot phase.

*Higher temperature if flames touch the walls.

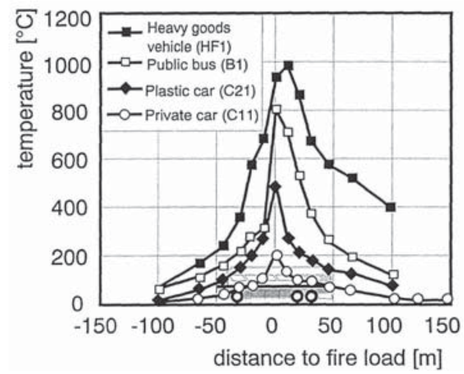

FIGURE 16 Maximum gas temperatures in the ceiling area of the tunnel during tests with road vehicles (*21*).

FIRE DEVELOPMENT BASED ON LITERATURE REVIEW

Combustible materials in a vehicle or tunnel are set on fire by an external ignition source. Energy is released and part of the solid matter of the fire material is converted into gases being part of the smoke. These gases mix with ambient tunnel air. The constant release of energy greatly heats up the mixture of combustion gases and air, forcing it upwards, the phenomena of buoyancy effect. There is also direct radiation from the flames. The heated gas–air mixture comes into contact with the ceiling and walls. The mixture conveys part of its heat to surrounding surfaces through radiation and thermal conduction and continues spreading it through the tunnel as smoke, with the temperature progressively declining as it moves away from the fire source. The thickness of the smoke and its concentration are reduced as it mixes with the tunnel air. The ability to escape the smoky environment depends on the smoke's concentration and the height of the smoke layer above the roadbed.

The combustion process efficiency depends on sufficient oxygen availability. The air stream caused by the fire often creates a suction effect that assures oxygen supply from the portals or shafts. This results in continuous feeding of the fire with oxygen, which allows for continuous heating of the fire materials, and possible re-ignition. The process continues until either the combustible material is completely burned or the fire extinguishing measures interrupt the burning process.

The growth and development of a fire will be influenced in its early stages by the ignition scenario and the fire performance of the materials. Fires can start developing inside vehicles or

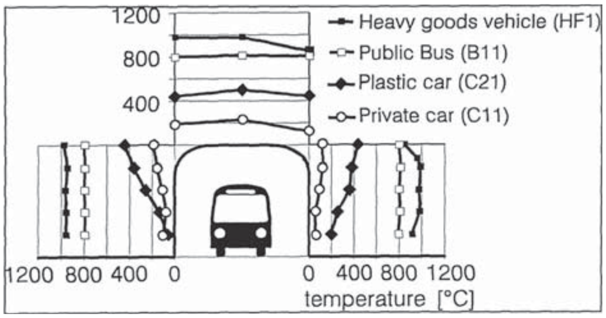

FIGURE 17 Maximum gas temperatures in the cross section of the tunnel during tests with road vehicles (*21*).

outside in the cargo container. As fires develop, heat builds up leading to elevated gas temperatures within the enclosure. The elevated temperatures will in turn have a significant impact on the growth rate of the fire. Elevated gas temperatures will pre-heat materials that have not been ignited and potentially accelerate flame spread. Gas temperatures in an enclosure can be affected by the size of the enclosure, the ventilation into the enclosure, and the FHRR (see Figure 17).

Development of fires inside vehicles is dependent on a number of factors including: (1) the fire performance of interior materials and features, (2) the fire performance of vehicle cargo, (3) the size and location of the initiating fire event or ignition scenario, (4) the size of the enclosure where the fire is located, and (5) the ventilation into the enclosure.

The specification of a design fire may include the following phases:

1. Incipient Phase, characterized by the initiating source such as smoldering or flaming fire.
2. Growth Phase, the period of propagation spread potentially leading to flashover or full fuel involvement.
3. Fully Developed Phase, the nominally steady ventilation or fuel-controlled burning.
4. Decay Phase, the period of declining fire severity.
5. Extinction Phase, the point at which no more heat energy is being released.

Figure 18 represents all phases of fire development.

A smoldering fire is caused by a combination of the following (input) parameters:

1. Nature of the fuel,
2. Limitation of ventilation, and
3. Strength of the ignition source.

The smoldering fire generally burns over a long period in limited ventilation conditions with insufficient oxygen to fully burn the fuel. It produces relatively low levels of heat, but considerable unburned combustibles and a higher concentration of smoke. This creates a relatively low visibility with large toxic products of combustion such as CO and soot (e.g., the burning of rubber tires of those vehicles involved in the fire). The relatively low temperatures generated create less buoyancy in the combustion products, and thus decreases the likelihood of smoke stratification under the tunnel roof as with hotter fires. Therefore, the principal hazards posed by a smoldering fire are high concentrations of CO and low visibility conditions. The construction and combustible contents of a vehicle, such as electrical fault or overheating parts in the engine compartment, could be a potential source of a smoldering fire in tunnels.

Pre-flashover fires include the incipient and growth phases and are of primary interest in life safety analyses. The growth

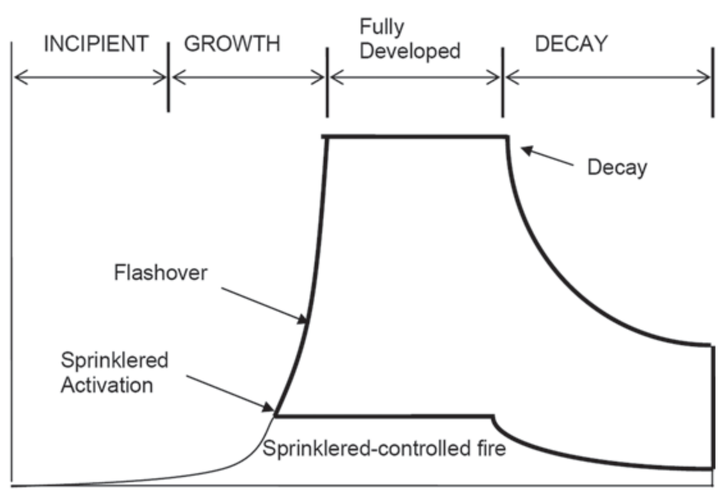

FIGURE 18 Simplified phases of fire development. *Note*: Sprinkler activation is shown as a representative example and its impact on fire development depends on its activation time and sprinkler system characteristics discussed later (*9*).

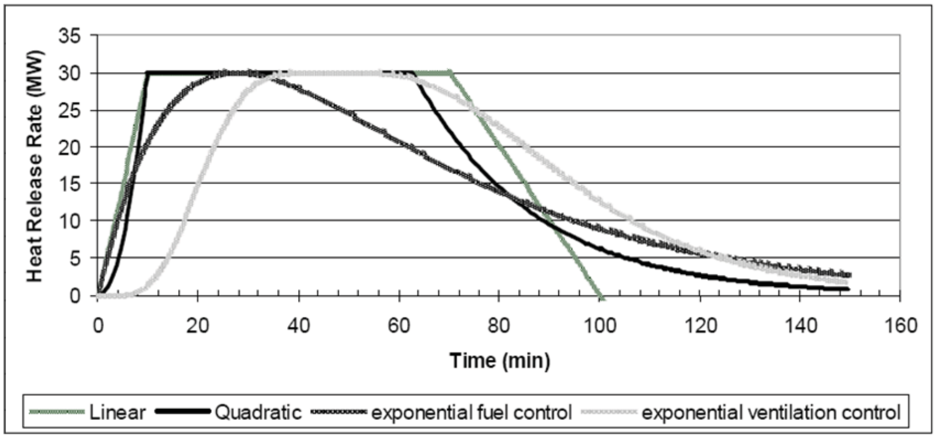

FIGURE 19 An example of fire development curves linear, quadratic, and exponential proposed as the result of UPTUN tests (*28*).

of a fire is dependent on fuel and the availability of oxygen for combustion. Typically, as the fire grows in size, the rate of growth accelerates. The rate of fire growth may be modified owing to compartment effects, radiative feedback, activation of sprinklers or the application of other suppressants, availability of fuel, and the availability of oxygen, among other factors. It is important to recognize that the total fuel load has little bearing on the rate of fire growth; however, the rate of fire growth is governed by the HRR of the individual fuel items burning.

There are numerous methods available to mathematically represent a design fire curve in tunnels. These include different types of fire growth rates; for example, linear growth ($a \cdot t$), quadratic growth ($a \cdot t^2$), or exponential growth (see Figure 19). An exponential or power-law is often used for characterizing the transient growth of the HRR. The most common is the "t^2 fire," where the HRR increases with the square of the time. These growth and decay functions can be combined with the maximum fire HRR to obtain the fire curve.

$$\text{Fire growth phase: } Q(t) = at^2 \text{ for } 0 < t < t_1;$$

Max HRR: $Q(t) = Q_{max}$ at $t = t_1$, where t_1 equals time when fire reaches its maximum HRR

$$\text{Decay phase: } Q(t) = Q_{\max} e^{-b(t-t_1)} - t > t_1$$

The quadratic growth curve is defined in the NFPA standards such as NFPA 204; they differ with:

- Ultrafast growth rate
- Fast growth rate
- Medium growth rate
- Slow growth rate.

Figure 20 represents different fire growth quadratic growth curves.

The ultrafast fire growth curve with the fire growth coefficient of 0.178 kW/s^2 meets most of the Runehamar Tunnel fire tests. An example of a design fire curve is shown in Figure 21. No allowance in Figure 21 was made for the possible spread of fire between vehicles, nor for the possible effects of under-ventilation on HRR development. If necessary, these effects

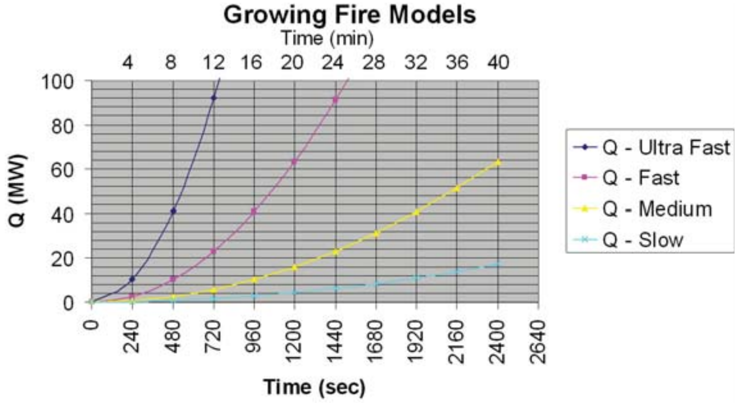

FIGURE 20 Quadratic fire growth curves based on NFPA 204 (2007).

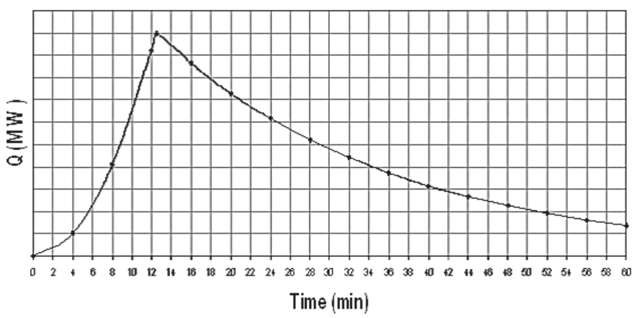

FIGURE 21 Example of design fire with curve decaying phase.

must be investigated separately. There are a limited number of studies found in the literature on fire spread between vehicles in tunnels.

If the fire remains isolated to the first item ignited, it will likely become fuel-controlled and decay. However, if the fire spreads to other combustibles, this can lead to the onset of rapid transition from a localized fire to the combustion of all exposed surfaces within the vehicle. This phenomenon is referred to as flashover, which is a sudden transition from localized to generalized burning.

The key characteristic of a fully developed fire is a significant steady-burning phase. Fully developed fires may refer to either fuel- or ventilation-limited fires. The transition from fuel- to ventilation-controlled burning occurs when

$$m_f = m_{ox}/s \tag{23}$$

where:

m_f and m_{ox} refer to the mass fraction of fuel and oxidant, respectively, and
s refers to the stoichiometric oxidant to fuel ratio (*8*).

The air-to-fuel equivalence ratio can be used to determine whether a fire is ventilation-controlled or fuel-controlled.

Usual tunnel fires are fuel-controlled fires; however, in a severe fire such as the Mont Blanc fire, with multiple vehicles involved, the fire was a ventilation-controlled (oxygen-limited) fire. If the base of the fire source is completely surrounded by vitiated air it may self-extinguish. The vitiated air, which is a mixture of air and combustion products, is usually composed of about 13% oxygen when the fire self-extinguishes such that the flammability limits were exceeded. However, this value can be to some extent temperature-dependent. Increasing temperature tends to lower the flammability limits.

If the air-to-fuel mass ratio is greater than or equal to the stoichiometric value, then the fire is assumed to be fuel-controlled and the HRR is directly proportional to the fuel mass loss rate. This can be exemplified by stating that the oxygen concentration in the gases flowing out of the compartment or the tunnel exit is greater than zero. The chemical HRR, Q (kW), which is directly proportional to the fuel mass loss rate, m_f (kg/s), can then be calculated using the following equation:

$$Q = m_f X H_T \tag{24}$$

where:

H_T is the net heat of complete combustion (kJ/kg), and
X is the ratio of the effective heat of combustion to net heat of complete combustion.

If the air-to-fuel mass ratio is less than the stoichiometric value, then the fire is defined as ventilation-controlled and the HRR, Q, is directly proportional to the mass flow rate of air (i.e., proportional to the oxygen supply) available for combustion. The following equation assumes complete combustion and that all the air, m_a, is consumed:

$$Q = m_a H_T / r \tag{25}$$

Where r is the stoichiometric coefficient for complete combustion.

A good indication of when a fire has become ventilation-controlled is when the ratio m_{co}/m_{co2} begins to increase considerably where m_{co} is the mass flow rate of CO and m_{co2} is the mass flow rate of carbon dioxide (CO_2). Tests show that the ratio m_{co}/m_{co2} increases exponentially as the fire becomes ventilation-controlled for diffusion flames of propane, propylene, and wood crib fires.

Fires that grow sufficiently large can reach flashover, where all of the items inside a vehicle or compartment ignite. Usually this phenomenon occurs during a short period and results in a rapid increase of HRR, gas temperatures, and production of combustion products. The largest HRRs are expected just after flashover occurs (post-flashover) and are often the basis for tunnel smoke control system designs. During this period, the HRR is driven by the oxygen flow and the fire is therefore often considered to be "ventilation controlled." However, the HRR history of a vehicle fire ought to include HRR information during all stages of the fire: the ignition or incipient phase, the growth phase, potentially the post-flashover phase, and the decay phase.

Before undertaking any fire scenario analysis, it is essential that the fundamental aspects of fire science and fire safety engineering, and limitations of the mathematical models used for hazard analysis are clearly understood.

Design fires, which are the basis of the design fire scenario analysis, are described in terms of variables used for the quantitative analysis. These variables typically include the HRR of the fire, yield of toxic species, and soot as functions of time. When the mathematical models are not able to predict the growth of the fire and it spreads to other objects within the tunnel traffic or any other part of the tunnel, such growth and spread needs to be specified by the analysis as part of the design fire or determined on experimental basis. A design fire scenario would typically define the ignition source and process, the growth of fire, the subsequent possible spread of fire, the interaction of the fire with its enclosure and environment, and its eventual decay and extinction.

1. Input characteristics

Each design fire scenario is represented by a unique occurrence of events and is the result of a particular set of circumstances associated with active and passive fire protection measures. Accordingly, a design fire scenario represents a particular combination of events associated with factors such as:

a. Type, size, and location of ignition source;
b. Type of fuel;
c. Fuel load density, fuel arrangement;
d. Type of fire;
e. Fire growth rate;
f. Fire's peak HRR;
g. Tunnel ventilation system;
h. External environment conditions;
i. Fire suppression;
j. Human intervention(s); and
k. Tunnel geometry.

Design fires are further characterized in terms of the following variables as functions of time:

a. Fire characteristics (flame length, air velocity, radiation, convection, temperatures).
b. Critical velocity to prevent backlayering (only relevant in longitudinal ventilated tunnels).
c. Toxic species (smoke) production rate.
d. Time to key events such as fire spread from one vehicle to the next.

Alternatively, design fires can be characterized by thermal actions on the tunnel structure and equipment, as well as in terms of time–temperature curves that depend on the emissivity of the fire, surface temperature, and emissivity of the walls. Table 24 and Figure 22 show the application of different design fire curves developed as the result of the UPTUN project.

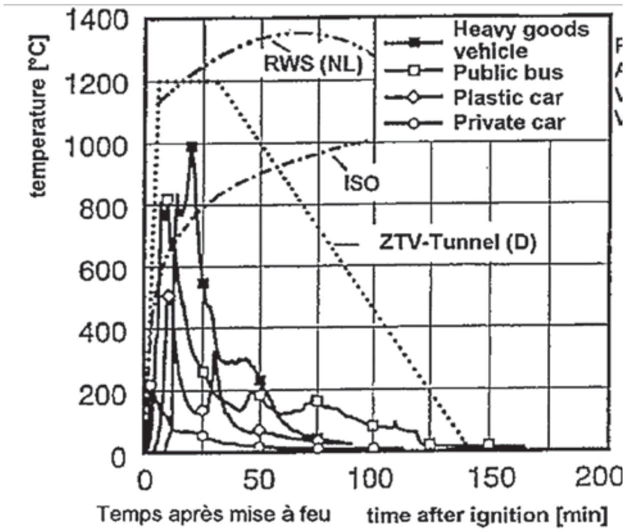

FIGURE 22 Fire scenario recommendation, UPTUN WP2 proposal by Ingason (*28*).

Many known actual tunnel fires and fire curves show a very fast development during the first 5 to 10 (sometimes 15) min. The gradient of temperature is rather steep and the emission of heat and smoke are important. Therefore, several temperature curves were presented that more closely correlate to important phases of a tunnel fire. NFPA 502 recognized the RWS curve. The standard reference curve for tunnel fires (the Rijkswaterstaat temperature–time curve) indicates temperatures exceeding 1,200°C (2,192°F) for a period of about 100 min and a maximum temperature of 1,350°C (2,462°F).

The duration of the hot phase of a fire normally covers a time interval of about 30 to 60 min after ignition stage, unless there are unusual circumstances such as a big pool fire caused by a gasoline tanker or a situation similar to the Mont Blanc fire. For a big gasoline tanker, the Dutch regulations indicate a hot phase of about 2 h. If fire trucks arrive on the scene quickly (within minutes) and deal with the fire effectively, the duration of the hot phase will be shorter. However, it is realized that access to such a fire will be difficult.

TABLE 24
FIRE SCENARIO RECOMMENDATION, UPTUN WP2 PROPOSAL BY INGASON

HRR MW			Road, Examples Vehicles	At the Fire Boundary
Risk to Life		5	1–2 cars	ISO 834
		10	Small van, 2–3 cars	ISO 834
		20	Big van, public bus, multiple vehicles	ISO 834
		30	Bus, empty HGV	ISO 834
	Risk to Construction	50	Combustibles load on truck	ISO 834
		70	HGV load with combustibles (approx. 4 tons)	HC
		100	HGV (average)	HC
		150	Loaded with easy comb. HGV (approx. 10 tons)	RWS
		200 or higher	Limited by oxygen, petrol tanker, multiple HGVs	RWS

Source: Ingason (*28*).

After the hot phase, it takes time for the fire to decay if it is not extinguished. The German ZTV Tunnel assumes that it can take about 110 min of linear temperature decaying. The EUREKA tests confirmed the duration of fires, but show a steeper decline of temperatures just after the hot phase. On the other hand, the Nihonzaka fire lasted for four days.

SUMMARY

The assessment of fire safety in tunnels is a complex issue, where broad multi-disciplinary knowledge and application of different physical models are necessary to explore the causes and development of fires to evaluate measures to prevent and reduce its consequences. The systems to take into account comprise:

- The occurrence and physics of fire development.
- The tunnel systems; that is,
  - Infrastructure and
  - Operation.
- Human behavior of users, operators, emergency services.
- Other factors influencing safety.

The first priority for fire design of all tunnels is to ensure:

- Prevention of critical events that may endanger human life, the environment, and the tunnel structure and installations.
- Self-rescue of people present in the tunnel at the time of the fire.
- Effective action by the rescue forces.
- Protection of the environment.
- Limitation of the material and structural damage.

Fire prevention measures reduce either the probability or the consequences of an incident in a tunnel. They are related to:

- Tunnel design and maintenance;
- Traffic and vehicles; and
- Notification, communication, operator, and rescue services.

Mitigation measures are conceived to limit the consequences once the ignition has taken place and developed into a fire. The mitigation measures may be related to:

- Reduction of the fire development,
- Reduction of the consequences to humans, and
- Reduction of the consequences to structure and equipment.

The fire safety engineering will normally involve the following steps:

- Qualitative design review:
  - Definition of objectives and safety criteria, with reference to performance-based standard requirements and coordination with the authorities having jurisdictions;
  - Definition of the tunnel system;
  - Identification of fire hazards;
  - Selection and definition of fire scenarios;
  - Identification of methods of analysis; and
  - Identification of design options.
- Quantitative analysis of design using the appropriate subsystems:
  - Fire ignition, development of heat and smoke;
  - Spread of fire, heat, and smoke;
  - Structural response to the fire;
  - Detection, activation, and suppression; and
  - Behavior of tunnel users and the influence of fire on life safety.
- Assessment of the outcome of the analysis and evaluation against criteria.

The acceptance criteria, which establish the adequacy of the design, can be developed according to the following approaches:

- Deterministic (including, when appropriate, safety factors).
- Probabilistic (risk-based used in European countries).
- Comparative (comparison of performance with accepted codes of practice).

A design fire is an idealization of a real fire that might occur. A design fire scenario is the interaction of the design fire with its environment, which includes the impact of the fire on the geometrical features of the tunnel, the ventilation and other fire safety systems in the tunnel, occupants, and other factors.

Nobody can precisely predict every fire scenario given the range of variables and people behavior. Therefore, the designer makes a number of assumptions to make sure that the design will save lives and retain structural integrity under most of the foreseeable fire scenarios.

For design purposes, it is necessary to choose fire characteristics corresponding to the traffic that uses a particular tunnel. Conditions, such as the allowance of transporting hazardous vehicles and materials, have to be taken into account.

Design fires in tunnels are usually given as the peak fire HRR. There is no common ground on how to calculate the HRR. One possibility is weighting of the burning components of a vehicle, the other is the analytical method. Some calculations incorporate burning efficiency, which means that the fire may not consume the entire heat load available. The leftover content is typically in the form of either a char residue or as soot and smoke particles displaced by the combustion gas stream.

The magnitude and development of fire depends on:

- Vehicle combustion load (often called the fuel load, which is usually greater than the potential fire size),

- Source of ignition,
- Intensity of ignition source,
- Distribution of fuel load in the vehicle,
- Fire propagation rate,
- Tunnel and its environment (including available oxygen), and
- Other factors discussed in the next chapters.

Studies showed that the fire growth rate is more important than the peak HRR when investigating the safety of people in the tunnel.

Fire duration can be determined by the amount of available combustible material. The amount of fuel is different for each study based on the type of vehicles, loads, and traffic patterns. The duration of the hot phase of a fire normally covers a time interval of about 30 to 60 min after ignition stage, unless there are unusual circumstances such as a big pool fire caused by a gasoline where a hot phase of about 2 h is considered.

The specification of a design fire may include the following phases:

1. Incipient Phase—characterized by the initiating source, such as a smoldering or flaming fire.
2. Growth Phase—the period of propagation spread, potentially leading to flashover or full fuel involvement.
3. Fully Developed Phase—the nominally steady ventilation or fuel-controlled burning.
4. Decay Phase—the period of declining fire severity.
5. Extinction Phase—the point at which no more heat energy is being released.

A smoldering fire is caused by a combination of the following (input) parameters:

1. Nature of fuel
2. Limitation of ventilation
3. Strength of the ignition source.

The principal hazards posed by a smoldering fire are high concentrations of CO and low visibility conditions.

Pre-flashover fires include the incipient and growth phases, and are of primary interest in life safety analyses. The growth of a fire is dependent on fuel and the availability of oxygen for combustion. Typically, as the fire grows in size, the rate of growth accelerates. The rate of fire growth may be modified owing to compartment effects, radiative feedback, activation of sprinklers or the application of other suppressants, availability of fuel, and the availability of oxygen, among other factors. It is important to recognize that the total fuel load has little bearing on the rate of fire growth; however, the rate of fire growth is governed by the HRR of the individual fuel items burning.

Quadratic growth curves are defined in the NFPA standards. They can be categorized as:

- Ultrafast growth rate
- Fast growth rate
- Medium growth rate
- Slow growth rate.

The ultrafast fire growth curve with the fire growth coefficient of 0.178 kW/s^2 meets most of the Runehamar Tunnel fire tests.

If the fire remains isolated to the first item ignited, the fire will likely become fuel-controlled and decay. However, if the fire spreads to other combustibles, this can lead to the onset of rapid transition from a localized fire to the combustion of all exposed surfaces within the vehicle. This phenomenon is referred to as flashover, which is a sudden transition from localized to generalized burning, where all of the items inside a vehicle or compartment ignite. Usually this phenomenon occurs during a short period and results in rapid increase of HRR, gas temperatures, and production of combustion products. The largest HRRs are expected just after flashover occurs (post-flashover) and are often the basis for tunnel smoke control system designs. During this period the HRR is driven by the oxygen flow and the fire is therefore often considered to be “ventilation controlled.”

The key characteristic of fully developed fires is a significant steady-burning phase. Fully developed fires may refer to either fuel- or ventilation-limited fires.

Usual tunnel fires are fuel-controlled fires; however, in a severe fire with multiple vehicles involved, the fire can be a ventilation-controlled (oxygen-limited) fire. There are a limited number of studies found in the literature on fire spread between vehicles in tunnels.

Almost all fires generate smoke. Smoke is a mixture of gases, fumes, and particles. Its generation is affected by the following factors:

- Possible reduced supply of oxygen to the fire site
- Heat release
- Heat convection
- Longitudinal slope
- Type of ventilation
- Dimensions of the traffic space and possible obstructions
- Thrust caused by any moving vehicles
- Meteorological influences (wind strength and direction).

The main design parameter is the smoke flow rate produced by the fire. The smoke flow rate varies nearly linearly with the HRR—from about 50 m^3/s (1,765.7 ft^3/s) at approximately 10 MW (34 MBtu/hr), to about 250 m^3/s (8,828.7 ft^3/s) at approximately 150 MW (512 MBtu/hr).

Smoke reduces visibility in tunnels. Visibility depends on:

- Smoke density,
- Tunnel lighting,
- Shape and color of objects and signs,
- Light absorption of smoke, and
- Toxicity of smoke (eyes irritating).

The dangerous nature of smoke gases in tunnel facilities not only results from the visibility obscuring effect but also from possible toxicity of gases including CO, CO_2, and other gases depending on the burning materials, especially toxicity caused by cargo. The mass generation of CO_2 can be estimated using a ratio of 0.1 kg/s per MW of HRR. A reasonable linear correlation between the production rates of CO_2 and CO was found at an average ratio of 0.051 with a standard deviation of ±0.015. The correlation of the smoke-dependent visibility measured by the OD and the concentration of CO_2 produces a linear relation when a correction for the smoke gas temperature is made.

A lack of sufficient experimental data and test results requires designers to make an assumption by replacing an actual vehicle fire with a pseudo-fuel. Different designers use different fuels and different values to approximate the actual fuel, which causes inconsistency in modeling and design results. There is a need to use actual (or mutually agreed upon) design values for fires involving HGVs, buses, cars, and tankers. Additional testing results are needed.

Tunnel fires significantly increase the air temperature in the tunnel roadway and in the exhaust air duct. Therefore, both the tunnel structure and ventilation equipment are exposed to the high smoke and gas temperatures. Different fire characteristics are needed depending on whether the purpose is to design the tunnel structure or the ventilation facilities.

- The design of structures for fire resistance is based on the temperature of the hot air (centigrade or Fahrenheit) and radiation heat versus time.
- The design of ventilation is based on the HRR (thermal power in megawatts or million British thermal units per hour) or the smoke release rate (flow at the temperature of the hot smoke in cubic meters per second) versus time.

The dependence on time is very important for evaluating the conditions at the beginning of the fire, taking into account the self-rescue phase (time for the fire department to arrive and get organized). Memorial Tunnel Fire Tests, EUREKA tests, and Runehamar Tunnel fire tests provided ample data that allow for the estimating of a maximum temperature experienced by the tunnel ventilation equipment and by the tunnel structure.

New energy carriers or vehicles transporting fuel for new energy carriers do not necessarily mean higher risks, but they do represent a new situation and imply new risks. These risks need to be evaluated and considered. The incidents analyzed show that new energy carriers can lead to explosions with catastrophic consequences when there is a fire, although it does not mean that all vehicles running on new energy carriers will explode when used or when exposed to fire. However, seeking the worst case scenarios is important when new energy carriers are developed. It is also important to realize that all risks are not eliminated by introducing PRDs. Safety systems do malfunction, especially in used vehicles. The outcome still depends on the design of these devices and on the fire scenario.

Hydrogen can be used either for ICE vehicles or fuel cell vehicles. Hydrogen cars generate fast, high rising flames that reach high temperatures and can lead to higher temperature ceiling flows and damage to tunnel structures. The oxygen-deficient hydrogen fire also poses the risk of flashover inside the tunnel and ventilation ducts. As a result of the nature of flame/fire development, tunnels with greater slopes and with horseshoe cross sections (compared with equivalent rectangular cross sections) present lower hazards. The aim of the HyTunnel European on-going project is to develop codes, standards, and regulations so that additional risks owing to the introduction of hydrogen vehicles into tunnels can be handled safely.

Electric cars that use batteries as an energy source are seen as the single most promising future energy carrier, in particular, for city traffic. Some countries have restrictions on the use of some energy carriers in confined spaces. Many of the restrictions can be related to LPG, which is also considered to be as an alternative fuel, together with LNG, CNG, hydrogen, propane, methanol, ethanol, and biodiesel in accordance with the U.S. Energy Policy Act of 2005. LPG and CNG vehicles are restricted in tunnels in New York, New Jersey, Massachusetts, Maryland, and Virginia, as well as in Italy, France, and Austria. However, there are no restrictions on LPG vehicles in tunnels in Japan and many other countries.

The issue of new energy carriers is very diverse and constitutes many different fields of research. There are a variety of views on how vehicles running on LPG, CNG, or similar fuels are treated and what safety measures are needed. It is important that restrictions are based on correct information that is based on additional systematic research on new energy carriers. It is also important to provide correct and detailed information concerning safety issues and the behavior of these energy carriers where a fire can develop. Unless this occurs in a timely manner, there is a risk that decisions will be based on too little or erroneous information. The concern was raised of possible gas detonation if tunnel air velocity is close to 0. Additional research and numerical modeling is needed to address the risk posed by alternative fuel carriers and structural protection against their fires or explosions. The risk to humans from explosions and from oxygen displacement may also be critical and needs to be studied.

CHAPTER TEN

COMPILATION OF DESIGN GUIDANCE, STANDARDS, AND REGULATIONS

Design guidance, regulations, standards, and reports developed around the world are shown in Table 25. This table was compiled from a review of different literature sources.

PIARC, NFPA, the United Nations (UN), European Union (EU) requirements and other international guidelines are well recognized around the world. EU Directive 2004/54/EC aims at ensuring a minimum level of safety for road users in tunnels in the trans-European network.

The U.K. *Design Manual for Roads and Bridges* (BD 78/99) covers the procedures required for the design of new and refurbished road tunnels (*53*). In addition, it provides guidance for the necessary equipment and the required operational and maintenance systems. PIARC is currently developing new recommendations on tunnel fire safety design that are scheduled to be released in 2011.

Traffic density and tunnel length is determined in the definition of the safety measures of many countries. This allows several countries to define tunnel categories (United Kingdom, Austria, Norway, France, Japan, and United States).

- The passenger exit and the emergency access for rescue staff generally are covered by national regulations. Inter-distances between escape routes vary from 100 to 400 m (328.1 to 1,312.3 ft); the European directive defines a maximum distance of 500 m (1,640.4 ft). NFPA 502 does not allow for emergency exits to be spaced more than 300 m (984.3 ft) apart, with spacing justified by engineering analysis. The spacing requirement for shelters is not as frequent; however, these must have an access way connected to the outside (France, European directive).
- In many countries, the drainage of flammable liquid appears to be a well-defined safety element, with civil engineering and geometry arrangements specially adapted.
- For safety equipment, ventilation and smoke control during a fire are considered fundamental and in most countries are defined by detailed guidelines. From these guidelines the following can be summarized: Mechanical ventilation is a necessity for long tunnels. The required air volumes and velocities or the objectives must be met according to the selected design fire (performance-based approach). Requirements are specified to prevent smoke penetrating emergency exits and rescue access.
- The tunnel, the emergency exits, and rescue access lighting are defined by a minimal assisted luminance level.
- The requirements for traffic signage, both outside and within the tunnel, and signage for pedestrian exit and rescue, are generally clearly outlined in the guidelines.
- Communication and alarm systems, such as emergency telephones and alarm push-buttons are generally considered to be the minimum basic elements. However, the required spacing varies from 50 to 250 m (164 to 820.2 ft); the value of 150 m (492.1 ft) is specified by the European directive. Requirements focused on the automatic alarms on equipment, automatic incident detection, fire or smoke detection, and on radio rebroadcast. The installation of loudspeakers within the tunnel itself is not common, but requested in the evacuation facilities or shelters for the users.
- For traffic regulation and monitoring equipment, measurements must be adapted to the surveillance level of the tunnel. Guidelines were primarily established to allow for quick detection of the traffic incidents, such as traffic speed, density measurement, video control, and the means for a quick closure of the tunnel. The thermographic portal detectors that locate abnormally hot trucks before they enter the tunnel are never prescribed.
- The requirements for an emergency power supply for the safety equipment are generally well-specified.
- Regarding fire fighting, the distribution of fire extinguishers and fire hydrants of sufficient capacity throughout the tunnel, as well as the presence of a water network and fire hydrants of sufficient capacity, are prescriptive. Several countries place hydrants every 150 and 250 m (492.1 and 820.2 ft), whereas the European directive notes the maximum value of 500 m (1,640.4 ft). The installation of a fixed fire suppression system is not imposed in any regulation.

The structure and equipment require ample fire requirements. The structural resistance requirements vary from very prescriptive requirements (Germany) to more or less performance-based criteria (France, Austria, and Norway). The criteria are given in terms of duration and specified fire curves or HRRs. Documented calculations are required in all guidelines. Equipment resistance to heat is specified by heat reaction or resistance. The European directive defines these requirements much less precisely than many national guidelines. The following gaps have been noted

TABLE 25
DESIGN GUIDANCE, REGULATIONS, STANDARDS, AND REPORTS DEVELOPED AROUND THE WORLD

	Country	Title	ID	Type	Publisher/Year
1	U.S.	NFPA 502	NFPA	Standard	2008 and proposal for 2011 edition
2	U.S.	*Prevention and Control of Highway Tunnel Fires*	U.S.DOT, FHWA	Report	FHWA.dot.gov (2002)
3	U.S.	*Underground Transportation Systems in Europe*	U.S.DOT, FHWA, AASHTO	Report	NCHRP 06.2006
4	U.S.	*Making Transportation Tunnels Safe and Secure*	TCRP, NCHRP	Report	*TCRP Report 86/NCHRP Report 525*
5	U.S.	*Enclosed Vehicular Facilities*	ASHRAE	Handbook	2011 (every 4 years)
6	UN	*Recommendations of the Group of Experts on Safety in Road Tunnels*	UN TRANS/AC.7.9	Report	Economic and Social Council, Inland Transport Committee (2001)
7	Australia	Fire Safety Guideline for Road Tunnels	AFAC	Guideline	Australian Fire Authority Council (2001)
8	Austria	Guidelines and Regulations for Road Tunnel Design	RVS, IBS	Guideline	Transportation and Road Research Association (2001)
9	Austria	Guidance document A-13 for fire safety in road tunnels	ÖBFV	Code (regulation)	Austrian fire department. document based on European Directive 2004AEA4/EC
10	France	Inter-ministry circular no. 2000-63 of 25 August 2000 relating to the safety of tunnels in the national highways network	Circular 2000t63A2; CETU, CNPP; INERIS	Government circular	Ministry for intra-structure, transport, spatial planning tourism, and the sea (2000)
11	France	Inter-ministerial circular no.2000-82 of 30 November 2000 concerning the regulation of traffic with dangerous goods in road tunnels of the national network	Circ2000-82N2	Governmental circular	Ministry for intra-structure, transport, spatial planning tourism, and the sea (2000)
12	France	Law no. 2002-3 of 3 January 2002 relative to safety of infrastructures and transport systems, etc.	Law2002-J2	Law	Law 2002-3, art. 2
13	France	Risk studies for road tunnels: Guide to methodology	ESD	Guidelines	Guide 2002

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TABLE 25
(*continued*)

14	Germany	Guidelines for equipment and operation of road tunnels	RABT, DMT, SOLIT, STUVA, VdS, VFDB	Guidelines	Road and Transportation Research Association
15	Germany	ZTV Additional Technical Conditions for the Construction of Road Tunnels - Part 1 Closed Construction - Part 2 Open Construction	ZTV–Tunnel	Technical addendum	1995 1999
16	Italy	Tunnel lighting	UNI–Milano U29000240	Guidelines	July 2003
17	Italy	Circular 6 Dec. 1999. Safety of Traffic in Road Tunnels with Particular Reference to Vehicles Transporting Dangerous Materials	Circular 06.12.1999	Governmental circular	1999
18	Italy	Functional and geometrical standard for construction of roads	Ministry of Infrastructure and Transport	Ministerial decree	General Inspectorate for Traffic and Road Safety
19	Japan	Design Principles, Vol. 3 (Tunnel) Part (4) (Tunnel Safety facilities)	—	Corporation guideline	Japan Highway Public Corporation (1998)
20	Japan	Installation Standards for Road Tunnel Emergency Facilities		Safety standards	Japan Highway Public Corporation
21	Korea	National Fire Safety Codes	NFSC	Code (regulation)	Korea National Emergency Management Agency
22	Korea	Guideline for Installation of Safety Facility in Road Tunnels	GIST	Guideline	Ministry of Construction & Transportation (2004)
23	Netherlands	Technical standards for the provisions and installations RWS curves	Rijkswaterstaat; TNO (UPTUN)	Guideline	Dutch Ministry of Transport and National Regulator
24	Norway	Norwegian design guide, roads, tunnels	Public Roads Administration, Directorate of Public Roads	Guideline/ manual issued by public authority	Handbook 021
25	Norway	Road Tunnels	Staten Vegvesen (SINTEF NBL)	Government guideline	Norwegian Public Roads Administration, Directorate of Public Roads (2004)
26	Norway	Risk analysis of fire in road tunnels	(Norwegian Council for	Guideline for a Norwegian	Issued by the Standardisation

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TABLE 25
(*continued*)

			Construction Standards)	Standard	Council (2000)
27	Russia	Construction Rules and Regulations (SNIP) # 32-04-97 “Railway and Road Tunnels”	SNIP	Guideline	State Construction Committee (GOSSTROI)
28	Spain	*Manual for the Design, Construction and Operation of Tunnels*	IOS-98	Manuals are effectively standards	Nov. 1998
29	Spain	Road Instruction, Norm, Alignment	IC	Norma 3.1	Dec. 1999
30	Spain	Road Instruction, Norm, Vertical signals	IC	Norma 8.1	Dec. 1999
31	Sweden	Tunnel 2004	Tunnel 2004	Guideline	Swedish National Road Administration (2004)
32	Sweden	*Comparison and Review of Safety Design Guidelines for Road Tunnels*	SP Report 2007:08	Report	SP Swedish National Testing and Research Institute Report 2007
33	Sweden	Model Scale Tunnel Fire Tests: Sprinkler	SP Report 2006:56	Report	SP Swedish National Testing and Research Institute Brandforskprojekt 406-021
34	Switzerland	Guidelines for the Design of Road Tunnels.	ASTRA (Swiss Federal Roads Office)	Guidelines by the federal roads office	2005 (updated)
35	Switzerland	*Ventilation of Road Tunnels, Selection of System, Design and Operation*	ASTRA (Swiss Federal Roads Office)	Guidelines	Federal roads office (2004)
36	UK	*Design Manual for Roads and Bridges, Vol. 2: Highway Structure Design* Section 2, Part 9, BD 78/99: Design of Road Tunnels	BD 78/99	Guideline and requirements	The Highway Agency (1999)
37	EU	Directive 2004/54/EC of the European parliament and the council	Directive 2004/54/EC	Code (regulation)	European parliament and the council (2004)
38	EU	European Tunnel Research Program	UPTUN; L-SURF	Recommendation	www.uptun.net; www.l-surf.org
39	PIARC	Fire and Smoke Control in Road Tunnels 05.05.B	PIARC	Recommendation	PIARC (1999)
40	PIARC	Road Tunnels: Operational Strategies for Emergency Ventilation	PIARC	Recommendation	PIARC (2008)
41	PIARC	Road Safety in	PIARC	Recommendation	PIARC (1995)

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TABLE 25
(*continued*)

		Tunnels 05.04.B			
42	PIARC	Integrated Approach to Road Tunnel Safety R07	PIARC	Recommendation	PIARC (2007) C3.3
43	NVF	Ventilation av Vägtunnelar (Ventilation of Road Tunnels) NVF Sub Committee 61: Tunnels	Nordic Road Technical Association	Report of a Nordic working group	NVF 1993
44	ASTRA	Tunnel Task Force, Final Report	Swiss Federal Roads Office	Recommenda-tions for improved safety	May 2000
45	PWRI/Japan	Road Tunnel Technology in Japan PWRI no. 3023	Public Works Research Institute	Technical Memorandum	Ministry of Construction, 1991
46	PWRI/Japan	State of the Road Tunnel Equipment Technology in Japan—Ventilation, Lighting, Safety Equipment Public Works PWRI Vol. 61	Public Works Research Institute	Technical Note	Ministry of Construction, 1993
47	PWRI/Japan	*Report on Survey and Research on Tunnel Ventilation Design Principles* (Tunnel Ventilation Design Principles—Draft)	Public Works Research Institute	Survey Report	Technology Centre of Metropolitan Expressway (1993)
48	European Thermal Network	*Fire in Tunnels*	FIT	Technical Report	Thermal Network FIT supported by European Community G1RT-CT-2001-05017

From numerous sources.
UN = United Nations; EU = Europan Union; PIARC = World Road Association (l'Association mondiale de la route).

- The regulations and guidance need to provide better consideration of the inter-activity of all systems that interact in a tunnel. Integrated approaches shall be applied to tunnel fire safety.
- Better identification with regard to human behavior of both tunnel users and operators is important, as well as identification of the means to improve safety.
- Consideration shall be given for technical innovations that allow more ambitious safety objectives.

TUNNEL VENTILATION AND INTERNATIONAL STANDARDS REQUIREMENTS

Ventilation for fire and smoke control requirements in the international standards are summarized based on the literature review conducted for this effort. When there is a fire, the following safety criteria have to be applied in the design:

1. The purpose of controlling the spread of smoke is to keep people in a smoke-free environment as long as possible. This can mean one or both of the following:
   - That either the smoke stratification must be kept intact, leaving more or less clean and breathable air underneath the smoke layer (applicable to bi-directional or congested unidirectional tunnels) or
   - That smoke must be completely pushed to one side of the fire (preferably applied to noncongested unidirectional tunnels where there are normally no people downstream of the fire).
2. People must be able to reach a safe place in a reasonably short time and cover a reasonably short distance. Emergency exits are provided whenever necessary.
3. The ventilation system must prevent smoke from spreading to uninvolved areas.
4. The ventilation system must be able to produce good conditions for fire fighting.
5. In the event of a fuel fire, secondary explosions resulting from incomplete combustion have to be avoided. Therefore, the ventilation system must be able to deliver enough air for the complete combustion or dilution of explosive gases. A suitable drainage system is provided to minimize the surface area where fuel evaporation takes place.

There are two categories of ventilation used in most tunnels: natural and mechanical. Appendix F1 (web-only) provides comparison tables on tunnel ventilation requirements in different national (including NFPA 502, 2008 edition) and international standards. It covers requirements for natural ventilation, transverse ventilation, and emergency exits pressurization.

Natural ventilation relies on natural phenomena and traffic piston effect to renew the air in the tunnel. This ventilation system can be very effective for the dilution of pollutants (especially for one-way tunnels); however, it is not possible to rely on natural ventilation for safety purposes. Indeed, in the event of a fire in a tunnel, traffic will most likely stop, and the ventilation is only provided by natural phenomena that could be only partially deterministic (as the chimney effect). However, the main component of the ventilation will be quite uncertain (as meteorological components) and therefore unreliable.

Naturally, ventilated tunnels rely primarily on atmospheric conditions to maintain airflow and provide a satisfactory environment. The main factor affecting the environment is the pressure differential created by variations in elevation, the ambient air temperature, or wind effects at the boundaries of the facility. Unfortunately, most of these factors are highly variable with time and, therefore, the resultant natural ventilation is neither reliable nor consistent.

Because of the number of different parameters that interfere in the choice to ventilate a tunnel or not (length, location, traffic, type of vehicles using the tunnel, and so forth), it is not possible at this moment to express universal recommendations about the limits of the natural ventilation, especially the allowable length without mechanical ventilation.

A tunnel that is long or experiences frequent adverse atmospheric conditions requires fan-based mechanical ventilation. Among the alternatives available for road tunnels are longitudinal and transverse ventilation.

Longitudinal ventilation introduces or removes air from the tunnel at a limited number of points, primarily creating longitudinal airflow along its length, from one portal to the other. Longitudinal ventilation can be accomplished either by injection, using central fans, using jet fans mounted within the tunnel, or a combination of injection and extraction at intermediate points.

In longitudinal ventilation systems, using jet fans or portal nozzles (often called a Saccardo system), a longitudinal airflow sweeps all exhaust gases from the entrance to the exit portal.

The only feasible way to evacuate smoke with longitudinal ventilation is by pushing it through the tunnel toward the portal. However, the airflow velocity necessary for such operation is the cause of turbulence and affects the smoke stratification downstream of the fire. This phenomenon is more evident at higher air velocities. The smoke stratification can also be disturbed by the longitudinal slope of the tunnel (especially when air flows downwards) and by vehicles.

Smoke from a fire in a tunnel with no slope will naturally tend to propagate in both directions owing to buoyancy effects. If the ventilation is in operation, the smoke will tend to be driven in the direction of the ventilation airflow. At low tunnel airflow speeds, the buoyancy-induced flow is not entirely overcome and some smoke will flow upstream, which is often termed "backlayering."

The backlayering distance may be defined as the distance from the fire where the upstream smoke velocity is eliminated by the tunnel ventilation flow. Hence, a backlayering distance of zero would imply that no smoke flows upstream. The tunnel air velocity required to achieve this condition is termed the "critical velocity."

Air velocity to prevent backlayering depends on the FHRR Q, the tunnel area A, and height H. Air velocity increases with the FHRR, but then levels off as the HRR increases.

The design of the ventilation system and its operation must take into consideration that, owing to the presence of the longitudinal airflow, the zone downstream of the fire is exposed to smoke and hot combustion gases. This can lead to suffocation or burns for users in this zone. Any possible design measure aiming for a safe escape from the dangerous section (fire area or downstream) must be taken. For this reason, the present UPTUN recommendations take into consideration the following cases.

A tunnel with one-way traffic not designed for queues (a nonurban area) has a ventilation design that can assume that drivers downstream of the fire are free to escape by means of their own cars, whereas drivers upstream will not. Tunnels located in nonurban areas are generally not situated in frequent congestion situations. Therefore, the relevant ventilation systems are generally not designed for queues. Nonurban tunnels, which are frequently congested, have instead to be designed for queues. The event of a fire ignited by vehicles involved in a secondary accident in the presence of other vehicles trapped downstream is possible, but the relevant probability is low. This case is almost never taken into account in the design phase. If necessary, the risk of such an occurrence can be reduced by automatic incident detection and a traffic control system.

The required longitudinal air velocities preventing smoke backlayering must be calculated by considering the following parameters. Meteorological parameters, especially longitudinal, can influence the performance of the ventilation systems. The ventilation system must have sufficient capacity to produce the required air velocity against a stated adverse wind pressure. The difference in pressure can be evaluated using the following simplified equation of Bernoulli:

$$\Delta\rho = \frac{1}{2}k\rho\omega^2 \quad (26)$$

where:

$\Delta\rho$ represents the pressure induced by wind,
ρ the air density,
ω the wind speed, and
k a design parameter that depends on the configuration of the portals.

This effect was studied by Blendermann (*54*) (see Figures 23 and 24 and Table 26):

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 or exiting the tunnel.

- The traffic condition must also be evaluated. When evaluating the necessary thrust in case of a fire, it must be assumed that a certain number of vehicles can be trapped in the tunnel and their presence reduces the performance of the ventilation system. The number of vehicles trapped can be assessed according to the design mix of traffic (percentage of passenger cars and heavy vehicles), the level, and the performance of the current road operation and traffic control system available for the tunnel.
- For the effects of fire on the air flow, several aspects must be taken into account:
  - In the event of a big fire, the high temperature induces an increase of air volume (resulting from 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 a tunnel with a steep grade, the chimney effect can be raised to significant values.
  - The decrease of air density results in the lowering of the driving force of the jet fans that work in the hot air.

The reversibility of the system can be helpful during the fire fighting phase.

When planning the reversing of the air, it must be taken into consideration that such operations can take a longer time, depending on the ventilation system, the tunnel geometry, the fans used, and other conditions.

The 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, the smoke already can have traveled several hundred meters. When the smoke layer flow is reversed, it will be spread over the whole cross section, whereas during the people evacuation phases it is important to maintain good visibility conditions. Therefore, only after everyone is out of the tunnel can the reversal of the air flow direction take place. The reversing can be evaluated in the event of a traffic jam inside the tunnel, but it must be a human choice, not an automatic configuration. Table 27 summarizes the recommended ventilation operation in case of fire.

In the case of twin tunnels, reversing the flow in the non-incident tunnel can prevent the circulation of smoke evacuated through the portal of the twin tunnel. Such circulation of smoke can also be prevented by civil engineering work (the distance between the twin portals, protection walls between portals, and so forth).

The ventilation system needs to be designed to meet the previous requirements in case of a fire. For the design and

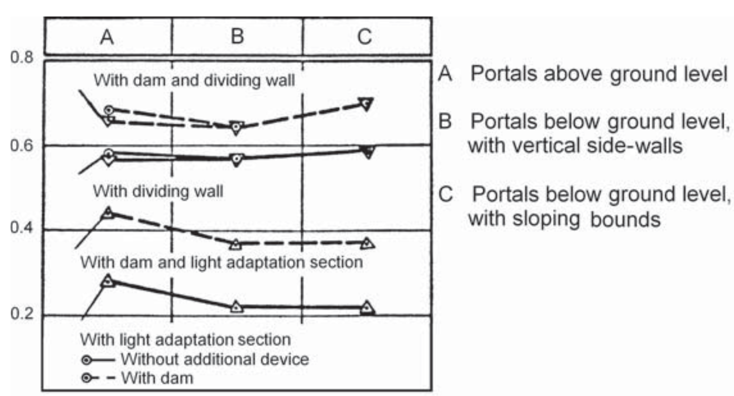

FIGURE 23 Mean Wind Pressure Coefficients (*54*).

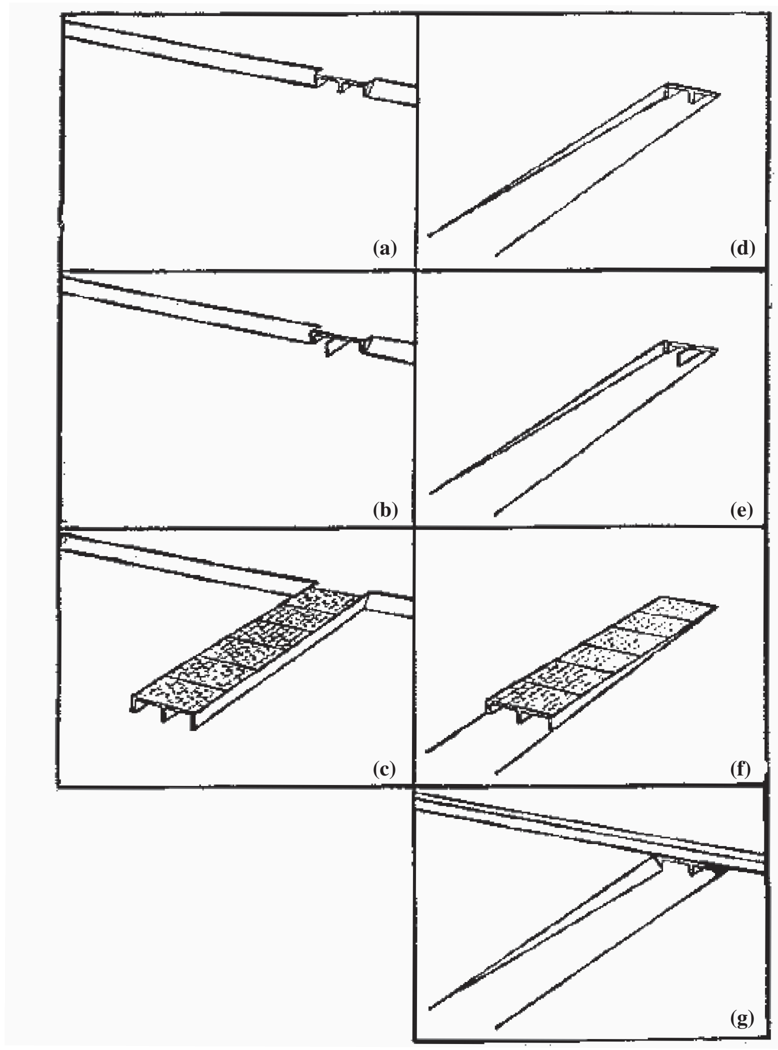

FIGURE 24 Some configurations of tunnel portals tested by Blendermann (*54*).

choice of all equipment it has to be taken into account that the hot smoke, traveling over the whole tunnel length, can seriously affect the installations (especially if the tunnel has a thermal insulation).

Cables, junction boxes, and all other nonprotected parts of the ventilation system have the same fire resistance as fans.

Special requirements shall be provided to jet fans operating in fire emergency:

- The strength of a normal aluminum blade falls quickly at high temperatures, although it depends on the type of alloy. When high air temperatures cannot be avoided, it is important that steel blades be chosen.
- Owing to high temperatures, the length of the blades grows more quickly than the housing enlarges. The blade tips then tend to block the rotation. Abrasive tips may be introduced or a larger distance between blades and housing provided.
- A normal fan motor has to be cooled by outside air to meet the cooling requirements. However, there are motors available that have a very high resistance without external cooling.
- All the auxiliary equipment as well as the wiring of the fan has to meet the air temperatures.

For these reasons, fans must be designed and built to withstand high temperatures.

There are several national standards for the heat resistance of fans, ranging from 250°C (482°F) for 1 h (Austria, the Netherlands, United Kingdom, and the United States), 250°C (482°F) for 1.5 h (France), 300°C (572°F) for 1 h (Norway and Sweden), and 400°C (752°F) for 1.5 h (France and Switzerland).

Where fans are distributed along the tunnel, a limited fan redundancy is suggested and can avoid the use of fireproof fans. In case of a fire, the temperature decreases rapidly when

TABLE 26
CONFIGURATION OF TUNNEL PORTALS TESTED BY BLENDERMANN

Additional Feature	Portal Above Ground Level	Portal Below Ground Level: With vertical side walls	Portal Below Ground Level: With sloping bounds
—	Figure 24 (a)	Figure 24 (d)	*
Dividing Wall	Figure 24 (b)	Figure 24 (e)	*
Light Adaptation Section	Figure 24 (c)	Figure 24 (f)	
Dam	*	*	Figure 24 (g)

Source: Blenderman (*54*).

the distance from the fire sight increases. It may be cost-effective to envisage the destruction of a few jet fans.

For a tunnel with one-way traffic, designed for queues (an urban area), the ventilation design must take into consideration that cars can likely stand to both sides of the fire because of the traffic. In urban areas it is usual to find stop-and-go traffic situations. Therefore, this case generally applies to urban tunnels of sufficient length.

For a tunnel with two-way traffic, where the vehicles run in both directions, it must be taken into consideration that in the event of a fire vehicles will generally be trapped on both sides of the fire.

Transverse ventilation uses both a supply duct system and an exhaust duct system to uniformly distribute supply air and collect vitiated air throughout the length of the tunnel. The supply and exhaust ducts are served by a series of fixed fans usually housed in a ventilation building or structure. A variant of this type of ventilation is semi-transverse ventilation, where either a supply or exhaust duct is used, but not both. The balance of airflow is made up within the tunnel portals.

The purpose of controlling the spread of smoke is to keep people as long as possible in a smoke-free environment. This means that the smoke stratification must be kept intact, leaving a more or less clear and breathable air underneath the smoke layer. The stratified smoke is taken out of the tunnel through exhaust openings located in the ceiling or at the top of the sidewalls. It is important to indicate that all supply air ducts and all extraction smoke ducts be very tight.

Continuous extraction into a return air duct is needed to remove a stratified smoke layer out of the tunnel without disturbing the stratification. However, the following conditions must be fulfilled:

- The longitudinal velocity of the tunnel air must be below 2 m/s (394 fpm) in the vicinity of the fire incidence zone. These were the observations in the Japanese full-scale tests. With higher velocities, the vertical turbulence in the shear layer between smoke and fresh air quickly cools the upper layer and the smoke then mixes over the entire cross section.
- With practically zero longitudinal air velocity, the smoke layer expands to both sides of the fire. The smoke spreads in a stratified way for up to 10 min, even without smoke extraction (depending on the tunnel and fire conditions). After this initial phase, smoke begins to mix over the entire cross section, unless by this time the extraction is in full operation.

With an air velocity of around 2 m/s (394 fpm), most of the smoke of a medium-size fire spreads to one side of the fire (limited backlayering) and starts mixing over the whole cross section at a distance of 400 to 600 m (1,312 to 1,968 ft) downstream of the fire site. This mixing over the cross section can also be prevented if the smoke extraction is activated early enough.

TABLE 27
LONGITUDINAL VENTILATION OPERATION IN TUNNELS WITH ONE-WAY AND TWO-WAY TRAFFIC

Longitudinal Ventilation	Evacuation Phases	Fire-fighting Phase
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 is quite small - no jet fans working in smoke zone	Avoid backlayering of smoke: - higher longitudinal velocity - direction of airflow adaptable
Two Tubes 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.	

- Vehicles standing in the longitudinal air flow increase strongly 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 induce a rotation of the longitudinal airflow, which tends to bring the smoke layer down to the road. This is the reason for the suggestion to throttle the fresh air rate from one-half to one-third of 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 because this increases the amount of smoke and tends to suppress the stratification.
- In reversible semi-transverse ventilation with the duct at the ceiling, the fresh air is added through ceiling openings in normal ventilation operation. If a fire occurs, as long as fresh air is supplied through ceiling openings, the smoke quantity increases by this amount and strong jets tend to bring the smoke down to the road surface. The conversion of the duct from supply to extraction must be done as quickly as possible.

Continuous or Concentrated Smoke Extraction (Single Point)

The traditional way to extract smoke is to use small ceiling openings distributed at short intervals throughout the tunnel. Another efficient way to remove smoke quickly out of the traffic space is to install large openings with remotely controlled dampers. They are normally in an open position where equal extraction is taking place over the whole tunnel length.

In case of a fire, the single-point extraction is achieved in the fire location by remote control of the dampers. Recent tests by CETU and the Memorial Tunnel fire tests have proven the advantages of this system. To facilitate maintenance, there are systems in use where the large dampers are held by a magnet in a 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.

Extraction Capacity

Once a design fire and its amount of smoke production 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 needs to be considered that in the first phase of the fire between the start of the smoke spreading and full operation of the exhaust system with large dampers, the smoke may have spread 1 km or more from the fire site depending on fire detection and ventilation system operation design. Therefore, it is not sufficient to only open a few exhaust openings near the fire, but a minimum exhaust rate along the whole ventilation section is suggested as well. An extraction strategy needs to be developed depending on the type of tunnel and its ventilation system.

The extraction capacity over the tunnel length that 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.

Single-point Exhaust Opening

The spreading of smoke over the entire length of the tunnel can be prevented by a large extraction of tunnel air directly above the traffic with suitable extraction ports. This system works best in conjunction with jet fans (see Figure 25) or portal (Saccardo) nozzles to localize smoke around openings and to prevent smoke from being driven by natural factors (such as wind and tunnel grade) and spreading along the tunnel. It is usually part of longitudinal ventilation with one or several central exhaust shafts.

The exhaust capacity and the longitudinal velocity created by the jet fans in the tunnel section filled with smoke have to be matched and controlled under operation; it does not matter whether the smoke is stratified or spread over the entire tunnel cross section. The recommended extraction value is based on a cross-sectional area times longitudinal velocity. The system must be able to extract a longitudinal airflow of 3 to 4 m/s (591 to 787 fpm) and the small air velocity in the following ventilation section toward the exhaust opening to prevent the spreading of smoke beyond the suction point.

Fresh Air Supply for Transverse Ventilation

During fires, it is suggested that the fresh air jets enter the tunnel near the road surface. Their exit velocity and the distances between the individual jets are small in order to obtain a uniform fresh air layer above the road.

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 velocity is reduced, which minimizes the air mixing with the smoke layer.

Fresh air jets entering from ceiling openings are unfavorable. When they enter the tunnel vertically, they destroy the smoke layer, induce smoke into the jet, and thus suppress smoke into the fresh air layer. The exit velocity of these ceiling supply air jets is to be small.

Fresh air jets entering from the ceiling are stopped immediately after the fire alarm sounds in the ventilation section.

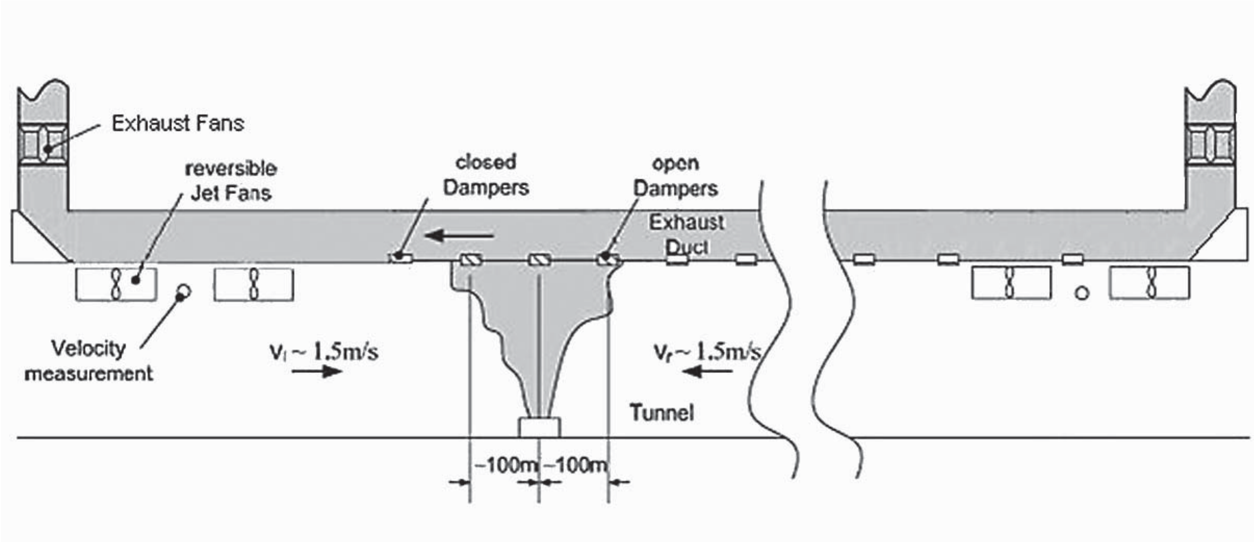

FIGURE 25 Tunnel with a single-point extraction system (*55*).

For longer tunnels, it is suggested that the fresh air outlets be positioned near the road surface.

Fans in the exhaust air duct are exposed to a mixture of very hot air from the immediate area surrounding the fire plus cooler air farther from the fire. This mixture of hot and cooler air then travels in the duct and gets more cooled down.

Tests in the Zwenberg Tunnel in Austria or in the Memorial Tunnel in the United States gave air temperatures at the fan below 250°C (482°F), even when the fire was very near the fan station. Memorial Tunnel test results are presented in Table 21 in chapter nine. A fire resistance of the fans to 250°C (482°F) could be considered sufficient for most of the fire events, but needs to be checked by design.

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

Control of Longitudinal Velocity for the Single-point Extraction System

To maintain smoke stratification, a low-speed longitudinal air velocity is required to push smoke to one side of the fire, which can be achieved by jet fans or Saccardo (portal) nozzles. However, the process of activating the required number of jet fans within a few minutes after fire ignition is complicated owing to the turbulent nature of tunnel airflow, large cross-section area, and changing winds and other natural factors. This requires air velocity measurements as average over cross section (*1*):

- Required accuracy ± 0.3 m/s,
- Short response time and time resolution, and
- 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.

The usual 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 a 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.

Whatever the means of controlling the longitudinal air velocity are, their operation has to be preprogrammed according to the location of the fire in the tunnel to ensure the opening of the required dampers and activation of required fans.

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 s. Reversible fans shall be capable of completing full rotational reversal within 90 s (NFPA 502). The emergency ventilation system shall be capable of reaching full operational mode within a maximum of 180 s of activation. Fans could be activated sequentially based on fire zones.

Emergency Exits Pressurization

NFPA 502 calls for a tenable environment provided in the means of egress during the evacuation phase. Emergency “exits” shall be pressurized in accordance with NFPA 92A. Appendix F1 (web-only) provides a comparison analysis of the pressurization requirements of emergency exits in the national and international standards.

TUNNEL FIRE PROTECTION, FIRE FIGHTING, AND INTERNATIONAL STANDARDS REQUIREMENTS

Tunnel fire protection standards requirements are summarized based on the literature review conducted for this report.

A tunnel fire is more effectively fought in its early stages. Some vehicles using the tunnel may carry fire fighting equipment; however, if such equipment is unavailable or insufficient then fire fighting equipment installed in the tunnel can be used. There could be cases when the installed equipment is insufficient to manage the fire size. Therefore, equipment such as fire hydrants and fire hose valves are used by the fire department.

Generally, hand-held extinguishers are provided in the tunnels; however, the required distances between them vary. Pressurized fire hydrants or fire hose valves are provided for most tunnels.

Appendix F2 (web-only) provides comparison tables on tunnel fire protection requirements in different national (including NFPA 502, 2008 edition) and international standards. It covers the fire fighting equipment (extinguisher, hose reels, and so forth) and water requirements. Typically, design fire size and physical tunnel configuration drive water flow and pressure requirements.

No European standards have requirements for installation of a fixed fire suppression system. Such requirements do exist in Japan and Australia:

- In Australia, AFAC (the Australian Fire Authorities Council) strongly advocates the installation of suitably designed, manually controlled deluge/sprinkler systems.
- In Japan, sprinkler systems are required for the following tunnels: Class AA, Class A tunnels more than 3000 m long and with average daily traffic of greater than 4,000 vehicles/day, and bi-directional tunnels. Sprinkler systems have been installed in more than 80 tunnels in Japan.

In Sweden, fixed fire suppression systems would be installed if it leads to a significantly raised level of safety for people according to risk analysis.

In Korea, the Gwangju Institute of Science and Technology (GIST) recommends installation of a fixed fire suppression system for tunnels that are more than 3000 m long with traffic flow of more than 60,000 vehicles × kilometers/day/tube for bi-directional tunnels or more than 90,000 vehicles × kilometers/day/tube for uni-directional tunnels. A sprinkler system has been installed in the Joogryeng Tunnel in Korea (*56*).

More discussions on fixed fire suppression systems is provided in chapter twelve of this report.

TUNNEL FIRE DETECTION, NOTIFICATION, AND INTERNATIONAL STANDARDS REQUIREMENTS

Fire-detection systems are necessary to alert tunnel operators of potentially unsafe conditions. The fire-detection principles are based on the parameters determined by the fire:

- Smoke
- Heat
- Flames (radiation).

There are a range of methods available to detect fire and smoke within road tunnels, including linear (line-type) heat detection, closed circuit television (CCTV) video image smoke detection, flame detection, smoke and heat detectors, and spot-type heat and smoke detection. Selections of fire-detection systems are made depending on the fire safety goals and objectives and the overall fire safety program. This includes notifying occupants to allow for safe evacuation, modifying tunnel operations, initiating a fire life safety systems operation, and notifying emergency responders. The key objective is prompt notification while preventing nuisance alarms. Some jurisdictions require that "listed devices" be used. This is a design challenge because there are few listed devices for tunnel application. Depending on the nature of the fire, either smoke, flame, or heat can start developing first. Consequently, multi-sensor alarm systems are better suited for automatic control.

The National Fire Alarm Code (NFPA 72 of 2010), PIARC (PIARC Technical Committee C3.3 2007, PIARC Technical Committee C3.3 2007, PIARC Technical Committee C3.3 2008) and several research projects provide additional information to assist with the development of detection system concepts and designs. The Fire Protection Research Foundation (FPRF) of the United States and the National Research Council (NRC) of Canada sponsored a two-year international research project to investigate available fire-detection technology suitable for tunnel application. The main objective idea of the study was to provide information for use in the development of performance criteria, guidelines, and specifications for tunnel fire-detection systems, and to be used for updating NFPA 502.

The NRC has conducted fire tests in a laboratory facility and performed CFD analyses to investigate the impact of various tunnel fire scenarios on the performance of fire-detection systems. They have also conducted full-scale fire tests in an operating road tunnel in Montreal in collaboration with the Ministry of Transportation of Quebec and in the Lincoln Tunnel in New York with the support of the Port Authority of New York and New Jersey. One of the objectives was to investigate the false alarm potential in a tunnel environment (*57*). A discussion of these methods along with some of the advantages and disadvantages for each system follows.

Linear (Line-type) Heat Detection

There are several types of line-type heat detectors in use today. The three main types are Analog (Integrating) Linear Heat Detectors, Digital Linear Heat Detectors, and Fiber Optic Linear Heat Detectors.

- Analog (Integrating Heat Detector) systems incorporate a multilayer cable. A core conductor is 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 predetermined 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.

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 promote the longevity of their systems; with a useful system life of approximately 30 years.

Disadvantages of linear heat detectors are that some require cable replacement after a fire. With tunnels typically being extremely large, with 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 to actuate. There are known bus tunnel events where there was a new linear heat detection system that was unable to detect fire. Considerations shall be given to a large ventilated tunnel volume, which makes fire detection difficult.

CCTV Video Image Smoke Detection

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 and security, as well as smoke and fire detection. Second, detection is based on real-time video images; therefore, each camera can cover a large area. Third, this technology is capable of detecting fires in moving vehicles. Fourth, emergency responders can be provided with real-time video information about a fire. The visuals can provide useful information such as fire size, source, and location, which can help operators and responders to 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 its ability to guide evacuation, rescue, and firefighting. Many tunnels are already equipped with VID systems for traffic management and security protection. Recent studies conducted by the FPRF at NFPA also showed that the VID fire-detection system was one of most promising detection technologies for the use in road tunnel protection.

A new generation of video detection technology is being developed. It includes volume sensors; meaning that it looks for fire and smoke within the entire observation space of the Internet protocol (IP) address of the camera. This fundamental advantage results in faster, reliable fire and smoke detection and, most importantly, provides a visual picture of the situation to the on-duty operator. Some cameras are both Underwriters Laboratory (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 (*58*). Use of camera-based detection systems may fulfill a multi-purpose regimen if the camera image can be used for security, traffic, and/or road conditions as well.

To prevent nuisance alarms, multiple detections and confirmations are required before notification or system activations 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. Designers will need 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 can be a disadvantage for other systems as well.

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 ultraviolet, infrared, combination ultraviolet/infrared, or multiple wavelengths infrared.

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 provide design flexibility when developing the system.

A disadvantage of these 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. Newer designs account for these interferences. As with many of other systems, detection can be delayed for shielded fires.

Spot Detection

A number of traditional smoke and heat detection systems can be 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 that draw air into the tube, which is then directed to the detector.
- There are many different types of heat detectors. Typically, detection is either by an abnormally high temperature; 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; therefore, there is no need to hire a specialized contractor. Compared with 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 trigger an alarm. A disadvantage of projected beam and duct-mounted detectors is that they are prone to nuisance alarms from diesel exhaust, which is almost always present in road tunnels.

Appendix F3 (web-only) provides comparison tables on tunnel fire smoke detection requirements in different national (including NFPA 502, 2008 edition) and international standards.

In a few national guidelines for road tunnels, there are values for the maximum detection time and degree of accuracy of fire location, including fire loads and airflow speed. Fire-detection time is a critical element in a tunnel fire event. Detection time depends on fire development and ventilation conditions and varies from 1 to 2.5 min. Maximum design detection time is directly related to fire development.

Table 28 provides requirements for fire-detection and fire alarm systems in road tunnels in various countries. The following can be concluded from this table:

- An alarm triggers no later than 60 s after ignition or at fire energy load not exceeding 5 MW.
- The fire alarm system shall respond to relatively low energy release rates of 1.5–5 MW (5–17 MBtu/hr), meaning that it must be capable of detecting fire at an early stage.
- Detection shall be made possible without restrictions to airflow speed in the tunnel up to 6 m/s (1,181 fpm).
- The accuracy of spotting the fire shall be between 20 and 50 m (65.6 and 164 ft).

Notification

Once the detection system is implemented, it can be used to provide automatic notification to any or all of the following: motorists, tunnel controllers, external agencies (traffic), emergency responders, etc.

A combination of fixed signage (speed, lane control, rescue zones) and variable message signs (VMS) provide a workable mix of visual instructions. The ability to use VMS as part of the preprogrammed emergency response scenario could prove helpful by stopping or slowing traffic; instructing motorists to turn off their vehicles, leave their keys, and exit; and direct them to clear a traffic lane and move to the optimum exit path.

Manual controls are always used for VMS. This allows incident command to communicate with emergency responders, motorists, and others if radio communication fails.

In addition to visible notifications, AM/FM radio override is common, but less effective given the reduced use of com-

TABLE 28
REQUIREMENTS FOR FIRE DETECTION AND FIRE ALARM SYSTEMS IN ROAD TUNNELS IN VARIOUS COUNTRIES

Standards	Detection Time	Fire Load	Detection Distance
Germany RABT 2003	<60 s at *V* air up to 6 m/s (1,181 fpm)	5 MW (17 MBtu/hr)	<50 m (164 ft)
CH 2001 Draft Directive on Road Tunnels	<60 s	Under review	<20 m (65.6 ft)
A RVS 9.282; 4.7.2002 9.261	*V* air up to 3 m/s (591 fpm) • Pre-alarm <60 s • Alarm <90 s; *V* air over 3 m/s (591 fpm) • Pre-alarm <120 s • Alarm <150 s	1.5 MW (5 MBtu/hr) and 3.5 MW (12 Btu/hr)	<10 m (32.8 ft)
NFPA 502	Addresses delay expected between ignition occurring and an alarm being initiated		<15 m (49.2 ft) (section 7.4.1.4)

Source: *Fire Protection in Vehicles and Tunnels for Public Support* (*59*).

mercial radio. Motorists can also be notified by a public address system once they are stopped and/or are out of their vehicles.

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 in some jurisdictions.

Conversely, using traffic controls to encourage motorists to continue to drive out of the tunnel may be important for tunnels that use 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 location, type of incident, conditions, and size of the incident. In turn, motorists can be instructed on what to do while emergency responders are enroute and tunnel staff initiate their emergency procedures (*60*).

Recently, intelligent evacuation notification technologies have been developed. One of the vendors uses electroluminescent lighting technology—an uninterrupted illuminated path to the exits with a continuous light source located near the walkway floor (E-Lume-A-Path) (*61*). Another vendor uses a multi-directional low-level light-emitting diode guidance system (*62*). The advantage of those technologies is that they can be preprogrammed to guide tunnel users in the correct direction depending on ventilation system response. This is especially important when complicated tunnel ventilation schemes are used to eliminate the wrong direction for evacuation.

TUNNEL EGRESS AND INTERNATIONAL STANDARDS REQUIREMENTS

Design provisions allow for safe evacuation during a fire when heat, smoke, and other products of combustion are released into the tunnel. Road tunnels are long, narrow, and underground, often with limited opportunities for stair cores to grade.

An emergency ventilation and fire suppression approach needs to be fully coordinated with the evacuation plan and the emergency response plan to provide a comprehensive overall life safety program for the tunnel. Egress systems must provide for safe evacuation under a wide range of emergency conditions. The emergency response plan must help facilitate evacuation and allow for appropriate responses to emergencies.

NFPA 502 does not allow for emergency exits or exit doors leading to exits to be spaced more than 300 m (1,000 ft) apart, with spacing justified by engineering analysis (*63*). For uni-directional traffic with a longitudinal ventilation system, this spacing will largely depend on the fire-detection system and its ability to detect fire as soon as possible such that ventilation can be activated to take smoke under control. They differ between self-rescue and assisted rescue from road tunnels. The majority of tunnel occupants are to rescue themselves during a fire event.

The following safety provisions have been applied in road tunnels worldwide (emergency passenger exit for users):

- Parallel escape tubes (egress corridor)
- Emergency cross passages to a parallel tunnel
- Shelter
- Direct pedestrian emergency exit (shafts, portals).

Appendix F4 (web-only) provides comparison tables on tunnel egress requirements in different national (including NFPA 502, 2008 edition) and international standards. It covers parallel escape tubes (Table F4-1), emergency cross passages (Table F4-2), shelters (Table F4-3), and direct pedestrian emergency exits (Table F4-4).

The comparison shows that *cross passage vehicle accesses* are required by the international standards, if possible, with a distance of approximately 1 km (3,280 ft). Turning areas shall be provided for long tunnels.

TUNNEL INCIDENT RESPONSE AND INTERNATIONAL STANDARDS REQUIREMENTS

The strategies adopted by the emergency services will recognize that an accident could rapidly escalate into a major incident and that a fast response is necessary. Tunnel rescue strategies in an emergency organization are planned, tested, and implemented. The tunnel operator coordinates the rescue strategy. A communication strategy is essential in tunnels.

Another important issue may be how to enter a particular tunnel in a safe way. Access times for the emergency services can be analyzed from different perspectives, including the location of the accident, turnout from the rescue station, turnout from another place or, if relevant, with reserve rescue forces when the normal forces are occupied.

The conditions within the tunnel and the exposure limits are identified and reviewed regularly so that proper precautions can be taken by rescue staff in a fire situation.

An emergency response plan is implemented for predefined events. This specifies the initial responses and so forth as defined in NFPA 502. Specific rescue effort plans are to be made based on the emergency response plans. Also instituted is a common information/media plan, which is agreed on between the emergency services and the tunnel operator. This will include providing information activities to media with the aim of keeping tunnel users and the media focused on safety aspects. The plan defines the information responsibilities during and after an accident; specifically, what information the tunnel operator can communicate. Also implemented is an education plan for all rescue staff, reflecting both the education of newly employed staff and refresher courses.

Likewise, an emergency service exercise plan is developed. These exercises can help to train new staff in communication or in the use of technical systems, such as fire hydrants. A common exercise plan between the emergency services and the tunnel operator staff is especially important.

The need for specific tunnel rescue facilities or equipment is analyzed and incorporated into the emergency services normal rescue facilities if it is found favorable from an efficient and safe rescue point of view.

In event of an accident, an efficient and clear alarm for resources is essential. When emergency services from different organizations are involved, special attention needs to be paid to the advantages of a computer-based alarm system, ensuring that all involved parties receive the same information.

The emergency services and the tunnel operator regularly perform common functional tests to demonstrate the technical functionality as well as the staff's ability to handle the equipment, such as the communication radios. It is essential that reliable, efficient, and fast communication be established for the rescue staff internally in the tunnel and externally with the rescue centers. The rescue forces must be able to communicate at least with their own control center during the incident to obtain the information about the cause of the event. They also need to be able to communicate between the inside of the tunnel and their control center.

Coordinated interventions are always to be performed according to the rescue plans, at least with regard to the number of resources for the initial rescue phase. The intervention follows plans concerning how and in which way to enter the tunnel. It also shows how to organize the rescue vehicle disposition, both inside the tunnel and for resources waiting outside the tunnel. Special consideration shall be given to means and methods to remove victims.

The following means for emergency access for rescue staff has been used in road tunnels worldwide:

- Separate emergency vehicular access gallery
- Cross-passage vehicular access
- Emergency lane
- Direct pedestrian access (lateral, upstairs, shaft)
- Turning areas
- Emergency services station at portals.

Appendix F5 (web-only) provides comparison tables on tunnel incident response requirements in different national and international standards. It covers a separate emergency vehicle gallery access (Table F5-1), cross-passage rescue vehicular access (Table F5-2), emergency lane (Table F5-3), direct pedestrian emergency access (lateral upstairs shaft) (Table F5-4), turning areas (Table F5-5), and emergency services station at portals (Table F5-6).

The size of a fire in a road tunnel will have a considerable effect on the ability of the Fire and Rescue Service to perform

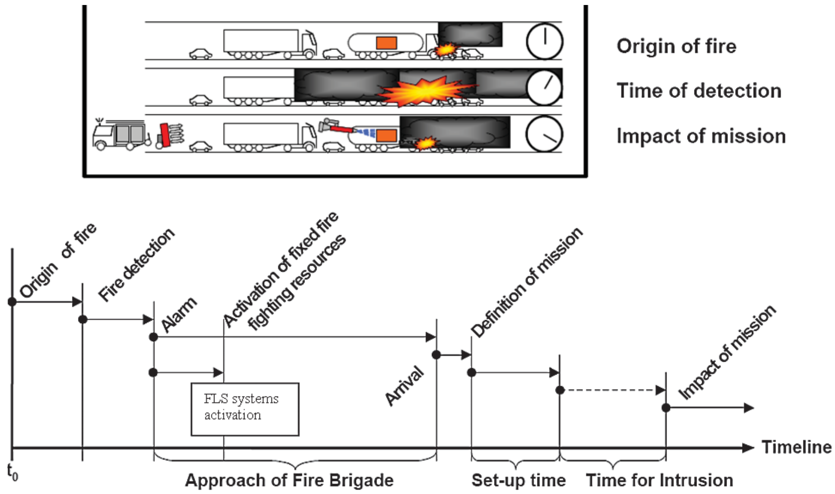

FIGURE 26 Fire fighting timeline (*14, 59*).

effective rescue and/or firefighting operations. When tackling fires in road tunnels, personnel and equipment need to be capable of dealing with fires of any magnitude.

Handling fires from private cars within twin-bore tunnels will almost always be within the capabilities of a firefighting force. However, the same fire in a single-bore tunnel could lead to considerable difficulties, depending on whether there is any airflow through the tunnel or whether there is a ventilation system capable of evacuating smoke from the fire or fixed fire suppression system available.

The factors that will set the capacity requirements for fighting a fire in a tunnel will be:

- The number of people that the rescue and fire services must assist to safety.
- The size of the fire and thus the temperature and thermal radiation power that will face the firefighters.
- The distance that the firefighters have to travel in a smoke-filled environment to reach the fire.

Fires in trucks, and especially gasoline tanker fires, are likely to reach output levels that it can be difficult to effectively contain.

The emergency response time is to be based on NFPA 1710. Figure 26 provides a tunnel fire fighting timeline.

How much water will be needed to put out the fire? This is an important question to answer, as it determines the number of jets used over a certain period of time. In turn, these jets require a certain number of firefighters, working under difficult conditions. The quantity of water needed to extinguish a vehicle fire in a tunnel, based on the extinguishing requirements for fires occurring in nonresidential buildings, is given in Table 29. In such instances, the firefighters had direct access to the fire. In this context, we need to remember that vehicle fires are particularly difficult to put out, which means that the following simplifications must be seen as an absolute minimum requirement in terms of water quantities.

The firefighters need to get close to a vehicle on fire to fight the fire because of the low ceiling of the tunnel. The water flow rate then has to be maintained for a significant period to put out the fire. It may take about 30 min, with at least the 1,250 l/min quantity of extinguishing water, to put out a fire in a truck. It would be possible to deal with fire gases using ventilation to increase the airflow; however, thermal radiation from the fire and from any residual back-

TABLE 29
ABSOLUTE MINIMUM WATER REQUIREMENTS FOR EXTINGUISHING A VEHICLE FIRE

Type of Vehicle	Fire Area (m^2)	Heat Release (MW)	Minimum Extinguishing Water Requirement (l/min)	Number of 360 l/min Jets
Private Car	10	5	226	1
Van	35	15	462	2
Truck	200	100	1,250	4

Sources: Rhodes and MacDonald (*20*) and Ingason et al. (*64*).

layering will be difficult to contend with. Development of some form of protection against thermal radiation is needed to assist tackling fires of this type, perhaps through the use of water mist jets or water curtain jets. Portable radiant barriers and vehicles already in the tunnel are used for protection from thermal radiation.

SUMMARY

Although each national and international standard provides specific information related to design fire, most of the specified information addresses the same general performance concerns. This summary highlights some safety features that have limited or no recognition in NFPA 502, or a difference in approaches between NFPA and most of the other international standards noted.

- For ventilation design in the event of a fuel fire, secondary explosions resulting from incomplete combustion need to be avoided. Therefore, the ventilation system must be able to deliver enough air for the complete combustion or dilution of explosive gases.
- PIARC documents and other international standards allow longitudinal ventilation in single-tube nonurban tunnels with 2-way traffic based on risk analysis relying on smoke stratification, although this is not recommended in the United States.
- No European standards have requirements for installation of a fixed fire suppression system. Such requirements exist in Japan and Australia:
  - In Australia, AFAC (the Australian Fire Authorities Council) strongly advocates the installation of suitably designed, manually controlled, deluge/sprinkler systems.
  - In Japan, sprinkler systems are required for Class AA tunnels, Class A tunnels more than 3000 m long and average daily traffic of more than 4,000 vehicles/day, and for bi-directional tunnels. Sprinkler systems have been installed in more than 80 tunnels in Japan.
  - In Sweden, fixed fire suppression systems would be installed if leading to a significantly raised level of safety for people according to risk analysis.
- Automatic fire detection with no allowance for manual fire detection is required by many international standards.
  - In a few national guidelines for road tunnels there are values for the maximum detection time and degree of accuracy of fire location, including fire loads and airflow speed. Fire-detection time is a critical element in a tunnel fire event. Detection time depends on fire development and ventilation conditions and varies from 1 to 2.5 min. Maximum design detection time is directly related to fire development.
  - A new generation of video detection technology is being developed. It includes volume sensors, which search for fire and smoke within the entire observation space of the IP address of the camera. This fundamental advantage results in faster, more reliable 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 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 many purposes if the camera image can be used for security, traffic, and/or road conditions.

Some international standards provide requirements in the tunnels for:

- Shelters
- Lay-bys
- Parallel escape tubes
- Separate emergency vehicular access gallery
- Cross-passage vehicular access
- Emergency lanes
- Direct pedestrian access (lateral, upstairs, shaft)
- Turning areas
- Emergency services station at portals.

Such requirements are not found in NFPA 502 and need additional studies of the experience from international standards.

Recently, intelligent evacuation notification technologies were developed using electroluminescent lighting technology—an uninterrupted illuminated path to the exits with a continuous light source located near the walkway floor or multi-directional low-level LED guidance system. The advantage of those technologies is that they can be preprogrammed to direct tunnel users in the right direction depending on ventilation system response. This is especially important when complicated tunnel ventilation schemes are used to eliminate the wrong direction for evacuation.

The following common gaps in the national and international standards and regulations were reported:

- The regulations and guidance need to provide better consideration of the interactivity of all systems that interact in a tunnel. Integrated approaches shall be applied to tunnel fire safety.
- Better identification with regard to human behavior of both tunnel users and operators, as well as identification of the means to improve safety.
- Consideration shall be given for technical innovations that allow more ambitious safety objectives.

CHAPTER ELEVEN

DESIGN FIRE SCENARIO FOR FIRE MODELING

The preceding chapter summarized information about fire dynamics and the release of heat and toxic gases based on the literature review. Design fire scenarios are discussed in chapter nine. A fire scenario is designed to provide an optimum fire life safety strategy for road tunnels. Design fire scenario discussion found in the literature is summarized in this chapter.

Fire scenarios are used for the following:

- Design of emergency exits,
- Choice of a fire-detection system,
- Choice of ventilation and fire suppression systems,
- Tunnel structural engineering,
- Specification requirements for tunnel structures and equipment,
- Operation of the tunnel, and
- Training of operators and first responders dealing with tunnel fires.

Fire scenarios usually include:

- Governing standards and guidelines;
- Description of the scenario;
- Thorough definition of the fire parameters (e.g., HRR/temperature versus time);
- Traffic scenario operation during fire emergency and tunnel ventilation operation;
- Guidelines for structural protection; and
- Specifications for materials, equipment, and structure.

In general, a broad spectrum of design fire scenarios is possible regarding their different goals (tunnel construction, equipment, tunnel operation). Therefore, the intention is to select the most important design fires and to prepare a short description of the fire scenarios, as shown in Table 30.

The fire HRR of a vehicle is one of the most important parameters. It is a main parameter in the calculation of critical velocity required to prevent backlayering of smoke and heat resulting from a fire, which in turn determines the airflow required to be delivered by a longitudinal system of ventilation. Among the possible fire loads the following vehicle fires are considered:

- Incidents with one vehicle (car, bus, truck, or gasoline tanker), and
- Collision incidents (a collision of two to three passenger cars, of a passenger car with a truck or bus, or of a bus with a truck).

The consequences of fire incidents in the following traffic situations are investigated according to the characteristics of the tunnel, such as an urban tunnel:

- Congested traffic (e.g., rush hours)
- Traffic jam (e.g., as a result of another accident)
- Flowing dense traffic (e.g., increased probability of multiple vehicle incidents).

The worst conditions may not be considered in the design or may not be correctly identified in design. For example, an assumption is usually made based on one incident at a time. In rear situation collisions, one incident may lead to another, such as when a blackout leads to a collision and then a fire event.

TIME–TEMPERATURE AND TIME-OF-TENABILITY CURVES

Time–Temperature Curve

If the specific fire scenario is known, such as with a truck with a specific load, it is recommended that a predetermined time–temperature curve be used when designing the tunnel structure and equipment.

Ideally, for a given fire scenario such as a single burning car, fire curves are used together with different exposure times. There are a number of known time–temperature curves used worldwide and these are presented in Figure 27.

The Dutch RWS–temperature curve includes the most stringent temperature requirements and is referenced in NFPA 502 for structural design, as shown in Figure 28. The RWS curve was developed by the Rijkswaterstaat, the Dutch Ministry of Transport, Public Works, and Water Management and applies to tunnels that are open to the transport of hazardous substances. This curve is based on the assumption that, in a worst case scenario, a 50 m^3 (1,765 ft^3) fuel, oil, or gasoline tanker fire with a fire load of 300 MW (1024 MBtu/hr) occurs, lasting up to 120 min (*65*). The RWS curve was based on the results of testing carried out by TNO (the Netherlands Organization for Applied Scientific Research) in 1979. Recently, the accu-

TABLE 30
EXAMPLES OF DESIGN FIRE SCENARIOS BASED ON INTERNATIONAL STANDARDS

Fire Scenarios		Important Requirements That Have to Be Met	Description of the Design Fire	Examples of Related Standards
No.	Purpose			
1	Test of construction material for immersed reinforced concrete tunnel structures, when passing of dangerous goods such as gasoline tankers is allowed	- Temperature at the interface of heat insulation panels and the concrete of the tunnel structure may not exceed 380°C (716°F). - Temperature at the steel reinforcement of the tunnel structure may not exceed 250°C (482°F).	- Time dependence of the temperature in the test oven according to the RWS curve. - Maximum temperature 1350°C (2462°F)—duration of the test burning: 2 h.	Dutch K.I.V.I. and Rijkswater-staat guidelines
2	Test of construction material for reinforced concrete tunnel structures when: - Dangerous good are allowed and - An immediate tunnel collapse or water intake is not anticipated	Temperature at the steel reinforcement of the tunnel structure may not exceed 300°C (572°F).	- Time dependence of the temperature in the test oven according to the ZTV Tunnel. - Maximum temperature 1200°C (2192°F)—duration of the test burning: 1 h 50 min (decline phase included).	ZTV-Tunnel, Germany
3	Test of jet fans for longitudinal ventilation systems	The jet fans and their related equipment for the electrical power supply must work at least 90 min, when hot air and smoke (temperature 250°C or 482°F) is flowing through them and surrounding them.	The test equipment must be able to deliver hot soot-enriched air at a temperature of 250°C (482°F) for at least 90 min.	RABT 1994, Germany
4	Designing of a longitudinal ventilation system with jet fans capable of controling a truck fire event with a calorific heat output of approximately 20 MW (68 MBtu/hr)	- Enough power to push the smoke in one direction of the tunnel (e.g., account for thrust loss of fans in hot air). - Choice of fan distribution along the tunnel for retaining enough fans for smoke control when some fans are damaged by the fire. - Availability of a fan operation mode which keeps emergency paths free from smoke.	- Fire data: see no. 2 - Smoke generation: approx. 60 m^3/s (2,119 ft^3/s) at a reference temperature of 300°C or 572°F.	RABT 1994, Germany

Source: PIARC (*21*).

racy of the RWS fire curve as a design fire curve for road tunnels was reconfirmed in the full-scale tests in the Runehamar Tunnel in Norway. The RWS curve and the temperature development table of the RWS fire curve is presented in the Annex (Explanatory material to Protection of Structural Elements) of NFPA 502 (see Figure 28).

The RWS curve is based on the level of temperature found when a fire occurs in an enclosed area, such as a tunnel, where there is little or no chance of heat dissipating into the surroundings. The RWS curve simulates the initial rapid growth of a fire using a fuel tanker as the source and the gradual drop in temperatures to be expected as the fuel load is burned off.

In reality, the construction may not be exposed to these time–temperature curves over the entire tunnel length. In a tunnel with a single vehicle fire, the tunnel lining is exposed locally to heat fluxes from the flame volume and the hot smoky gases.

In a tunnel accident with multiple vehicles, the fire spreads from one vehicle to the next resulting in different heat exposures to the tunnel lining depending on time, location, fuel load, and oxygen available. The fire moves within the tunnel in a dynamic manner and the heat fluxes to the linings vary depending on the origin of the fire, the ventilation rate, the type and amount of fuel (HRR), and the size of the cross section.

The gas temperature, the surrounding wall temperatures, the emissivity of the hot gases in the vicinity of the fire, and the surface temperature of the linings govern the net heat flux at the surface of the linings. The net heat flux to the linings will in turn govern the temperature rise inside the lining material.

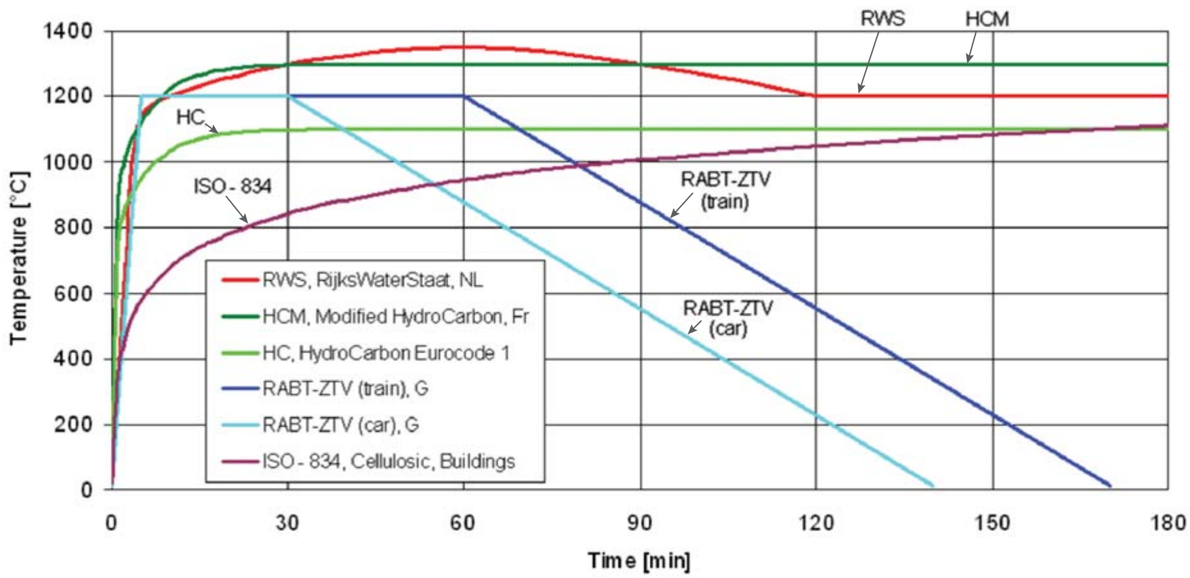

FIGURE 27 Time temperature curves (*65*).

The net heat flux q_s'' to the lining can be estimated by the following equation:

$$q_s'' = \varepsilon_g \sigma T_{g4} + (1-\varepsilon_g)\sigma T_{wall4} - \sigma T_{lin4} + hs(T_g - T_{lin}) \quad (27)$$

where:

q_s'' is the net heat flux to the linings,
ε_g is the emissivity of the hot gas,
hs is the convective heat transfer coefficient,
T_g is the gas temperature,
T_{wall} is the surrounding wall and floor temperatures, and
T_{lin} is the lining temperature where q_s'' is determined.

The incident thermal radiation from the fire to the tunnel lining is highly dependent on the geometry of the flame volume and its smokiness. The flame volume and its geometry are dependent on the HRR and ventilation conditions within the tunnel. The fraction of the flame radiant heat flux of the total heat release varies for most fuels and is between 0.25 and 0.4. For large tunnel fires, the tunnel linings in the vicinity of the fire are primarily affected by this incident flame radiant heat flux.

The project shall develop a time-of-tenability criteria based on the design maximum HRR. This maximum HRR may differ from 300 MW (1024 MBtu/hr) and gasoline tankers may

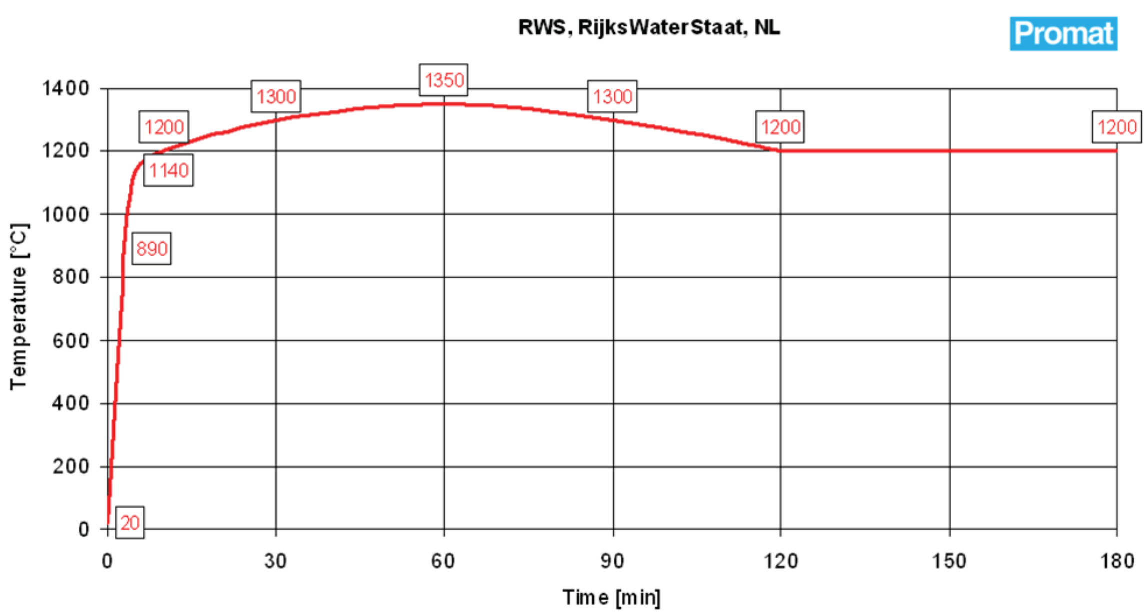

FIGURE 28 RWS curve (*65*).

not be allowed to travel through the tunnel (conditions at which the RWS curve was obtained).

Simple heat transfer equations do not allow for the making of a direct correlation between the time–temperature curve and the time–heat release curve. It appears that the known fire growth rates follow the super fast (highest increasing rate measured) temperature rise in the time–temperature curves. However, the use of HRR curves for the design is often allowed.

When using HRRs instead of time–temperature curves for calculating structural stresses resulting from a fire, a super fast increase of the HRR is to be used as it was observed with the Runehamar tests in Norway in late 2003. This phase is followed by a maximum design HRR according to the type of vehicle investigated.

The HRR within this scenario will be determined by the type of load that is allowed to pass through the tunnel as well as by the ventilation and fire suppression conditions, if applicable.

Following the decay of the fire, a linear or steeper decrease is used. The duration of the maximum HRR can be determined by using the burning load and type of fire suppression.

At the very least, the equipment must be able to function for the duration of the anticipated escape and rescue time. It must be considered that equipment in the direct fire zone may not withstand the fire for an extended amount of time.

Time-of-Tenability

For fire life safety an integrated approach is to be taken. Time-of-tenability can be understood by analyzing the entire system with all components working together.

To develop a time-of-tenability final curve the project must develop:

- A fire HRR curve as a function of time.
- A design evacuation (egress) curve as a function of time.
- A design systems response curve as a function of time.

This time line is illustrated in Figure 29.

The development of a fire, or the fire heat release curve, was discussed in the previous chapters and is a function of:

- Maximum FHRR,
- Fire growth rate (quadratic curve for either super fast, fast, medium, slow fire growth rate), and
- Fire decay rate.

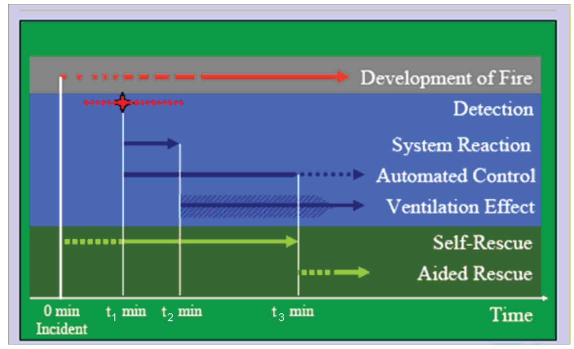

FIGURE 29 Fire emergency timetable (*6*, *66*).

EMERGENCY EGRESS TIMELINE

The egress timeline depends heavily on human behavior. Human behavior in a tunnel fire emergency can be a complicated. Unfortunately, in general, people tend to do the wrong thing in the event of a tunnel fire, such as staying inside their cars instead of heading for the emergency exits.

Intelligent Transportation Systems (ITS), warning motorists of any impending danger and providing them with valuable early directions, could be the extremely helpful.

Significant research has attempted to address such issues as to why people in vehicles in tunnels do not leave their cars and escape, but instead end up dying? Why do some people leave their vehicles and then return to them when the fire grows? Educating people and notifying them of danger is a separate subject. For design purposes, there is a need to assume that people will realize the danger, be notified to evacuate, make the correct decision on the direction for evacuation, and go to the point of safety. However, this may not happen immediately and some reaction time will be needed in realizing the danger of the situation.

It could be assumed that occupants of vehicles will have noticed the fire event within 30 to 60 s of ignition if the fire is rapidly developed. After that, there is some reaction time needed to make a decision. The project may consider that people will not move until they hear an alarm and get direction from the operator to evacuate. In addition, it is necessary to add times for detecting and alerting, reaction and leaving the vehicles, and walking to a safe place, to know if people can escape the fire safely. The sum of detection and alerting times depends on the type of fire detection and how the information is given to people in their vehicles. Therefore, this can take 2 to 5 min in manned tunnels.

The sum of the reaction times and leaving the vehicle is also difficult to estimate. For example, it takes longer for passengers to escape a bus than a car. Therefore, the sum of these times may vary between 30 s and 5 min.

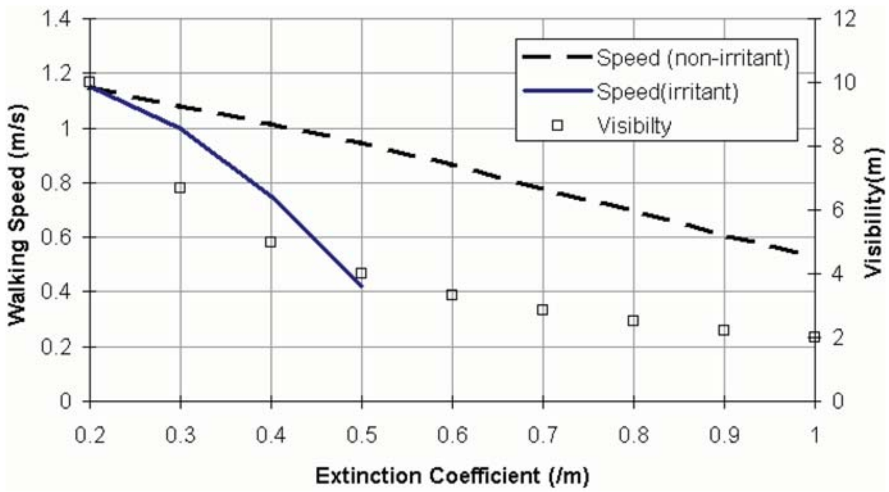

FIGURE 30 Walking speed in irritating and nonirritating smoke (*9*).

It is especially important when considering evacuation from a bus. A German study, *Fire Protection in Vehicles and Tunnels for Public Transport* (*59*) cites 2 min as the maximum period of time acceptable for evacuating a bus. Other studies report that 3 min is the expected time to fully empty a loaded transit bus.

Walking speeds can also vary. Depending on age and state of health, people can walk at a speed from 1 to 1.6 m/s (197 to 315 fpm).

A series of experiments exploring the relationship between visibility in smoke and evacuation movement were conducted in a smoke-filled corridor 20 m (65.6 ft) long. The experimental population consisted of 17 females and 14 males, ranging from 20 to 51 years in age. Experiments were conducted using both nonirritant and irritant smoke. People were asked to travel from one end of the corridor to the other, identifying when they could see a fire exit sign. Both the irritancy and the density of the smoke affected the volunteer's walking speed. Figure 30 shows the gradual decline of the recorded walking speed through nonirritant smoke as the density of the smoke is increased, whereas in irritant smoke the gradient is far steeper. This was explained as being caused by the erratic movement of the volunteers owing to their inability to keep their eyes open. The volunteers attempted to compensate for this lack of orientation by using the walls for guidance.

Results suggest that in nonirritant smoke with an OD of 0.43 m (1.4 ft) (extinction coefficient of 1.0) walking speeds are reduced to 0.5 m/s (98.4 fpm). However, in irritant smoke at an OD of 0.22 m (0.72 ft) (extinction coefficient of 0.5), the walking speed is reduced to 0.4 m/s (78.7 fpm) (see Figure 30).

PIARC suggests that the walking speed in a smoky environment (with some level of visibility) is from 0.5 m/s (98.4 fpm) to 1.5 m/s (295.3 fpm) (*21*). Consideration needs to be made for people with mobility impairments.

The speed of movement for those who are mobility impaired was tested in Leipzig on the station's platform (*60*) and is presented in Table 31. This table shows that a walking speed of 0.5 m/s (98.4 fpm) can be considered as a reasonably good estimate.

Depending on the number of evacuees (occupant load), a bottleneck may form approaching the cross passages or egress stairs. It is not possible to take fire and smoke under control immediately. Therefore, for several minutes, fire and smoke will be driven by natural factors. This is the most important

TABLE 31
SPEED OF MOVEMENT AND EVACUATION TIMES OF MOBILITY-IMPAIRED PEOPLE

Users	Speed of Movement	Movement Time Distance 110 m (360 ft)
Wheelchair Users	0.7 m/s (138 fpm)	150 s
People with Prams/Carriages	1.1 m/s (217 fpm)	95 s
People with Walking Aids	0.6 m/s (118 fpm)	175 s
People with Infants	0.55 m/s (108 fpm)	190 s

Source: *Fire Protection in Vehicles and Tunnels for Public Support* (*59*).

TABLE 32
EXAMPLE OF PROJECT ESTABLISHED TIME-OF-TENABILITY CURVE

Self-Rescue	FLS Systems Activation
A. Make a decision to evacuate	1. Detection Time
B. Disembark the bus	2. Operator Reaction Time (alarm)
C. Walk away from the fire effected zone	3. Systems Activation
D. Reach cross passage	4. All Fans Activated
	5. Ventilation Mode in Full Operation

time for evacuation. The sooner smoke and fire will be taken under control the sooner there will be a tenable environment for evacuation. The distance that people can safely travel to an exit depends on the fire development and system activation. The primary role in system activation is fire detection. Thus, spacing between cross passages will largely depend on the fire-detection system. For example, if the fire is not detected, the smoke control systems are not activated and spacing between cross passages would be determined based on the speed of the loss of visibility and smoke growth in the path of evacuation.

Application of the tenability criteria at the perimeter of a fire is impractical. The zone of tenability is defined by applying it outside the boundary, away from the perimeter of the fire. This distance will depend on the FHRR.

EQUIPMENT ACTIVATION TIMELINE

It was discussed in previous chapters that it is not possible to achieve a fully operating mode for all fire fighting equipment instantaneously. Equipment activation time consists of the following phases for supervised tunnels:

1. Fire-detection time (from 2 to 3 min if reliable automatic fire-detection system is installed).
2. Fire alarm and operator reaction time (from 60 to 90 s).
3. Time to bring the first group of fans to full speed (60 s for unidirectional and 90 s for reverse mode—NFPA 502).
4. Activate fixed fire suppression system if desired (30 s–60 s if wet).
5. Achieve a full operational mode for ventilation system (180 s).

For the unmanned tunnels, the system is usually designed to be fully automatic or operated by the local fire department.

In any case, the first and the most critical element of the system is fire detection. Although many tunnels still rely on manual fire detection, this needs to be revisited. Operators may require help in detecting a fire, which would allow them to take appropriate actions in a timely manner.

COMBINED CURVE FOR EVACUATION AND SYSTEM ACTIVATION

Based on fire development, emergency egress, and the equipment activation timeline, it is possible to create a combined heat–egress system activation time curve similar to the one presented in Table 32. This curve allows one to analyze the design HRR at every evacuation and system activation phase and to make the correct decisions.

When the evacuation phase is concluded, fire fighting must be facilitated by proper smoke handling. A basic requirement is to provide maximum opportunity for the fire fighting access in minimum smoke. During evacuation, the direction of smoke flow must not change. With the arrival of the fire department, it can be decided on-site which fan control is the best to facilitate the fire fighting.

The time-of-tenability graph can be prepared as the result of fire life safety systems design and CFD analysis. A sample of this graph is shown in Figure 31. This graph is called a tenability map and shows all time steps discussed earlier and the resulting impact on casualties and tunnel structure. It allows one to predict for how long the environment will be tenable

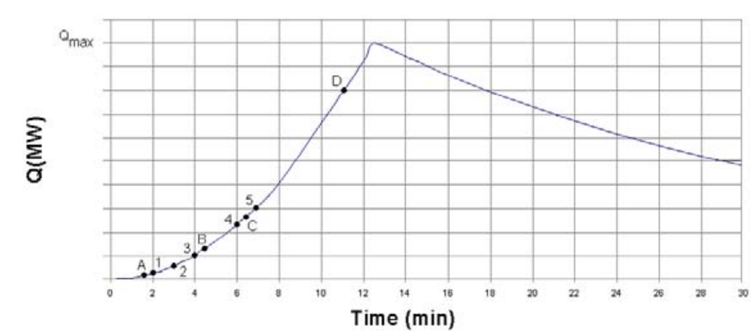

FIGURE 31 Example of project established time-of-tenability curve (*67*).

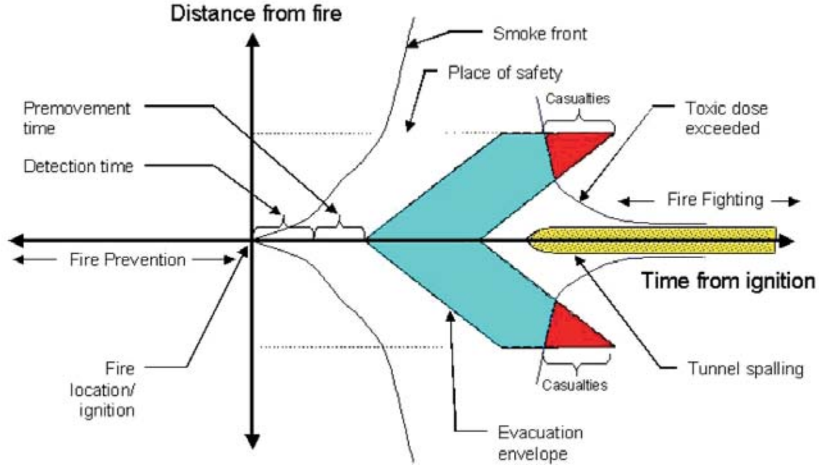

FIGURE 32 Time-of-tenability sample graph with no ventilation (*67*).

in the tunnel and helps to decide what needs to be done to achieve fire life safety goals. In this figure the pre-movement time is the time between discovery of a fire and the start of egress travel.

Figure 32 illustrates how longer detection and pre-movement times with greater fire hazards can lead to casualties. Figure 33 illustrates the impact of longitudinal ventilation on fire life safety and structural protection. It shows no casualties and much safer fire fighting. Tunnel spalling danger is eliminated on the upstream side and significantly reduced on the downstream side.

SUMMARY

A fire scenario must be designed to get an optimum fire life safety strategy for road tunnels. Fire scenarios are used for the following:

- Design of emergency exits
- Choice of a fire-detection system
- Choice of ventilation and fire suppression systems
- Tunnel structural engineering
- Specification requirements for tunnel structures and equipment
- Operation of the tunnel
- Training of operators and first responders dealing with tunnel fires.

Fire scenarios usually include:

- Governing standards and guidelines
- Description of the scenario
- Thorough definition of the fire parameters (e.g., HRR/temperature versus time)
- Traffic scenario operation during fire emergency and tunnel ventilation operation

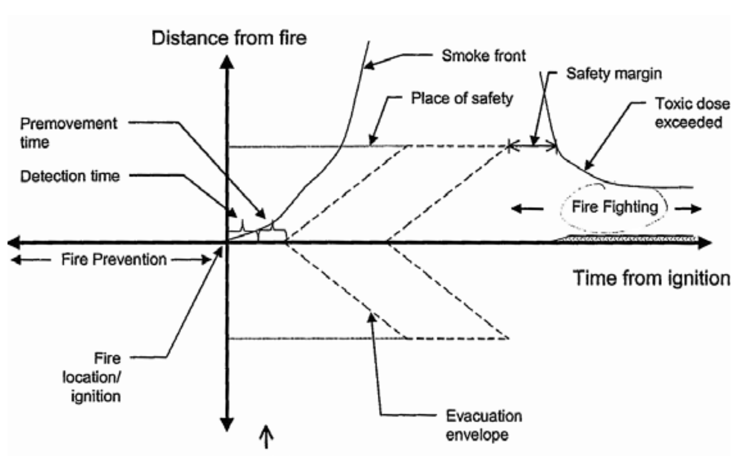

FIGURE 33 Time-of-tenability sample graph with longitudinal ventilation (*35*, *68*).

- Guidelines for structural protection
- Specifications for materials, equipment, and structure.

If the specific fire scenario is known, such as with a truck with a specific load, it is suggested that a predetermined *time–temperature curve* be used when designing the tunnel structure and equipment. There is a number of known time–temperature curves used worldwide. The Dutch RWS temperature curve includes the most stringent temperature requirements and is referenced in NFPA 502 for structural design. This curve is based on the assumption that, in a worst-case scenario, a 50 m^3 (1,765 ft^3) fuel, oil, or gasoline tanker fire with a fire load of 300 MW (1024 MBtu/hr) occurs, lasting up to 120 min.

Simple heat transfer equations do not allow for the making of a direct correlation between the time–temperature curve and the time–heat release curve. It appears that the known fire growth rates follow the super fast (highest increasing rate measured) temperature rise in the time–temperature curves. However, the use of HRR curves is often allowed for the design.

For fire life safety an integrated approach is to be taken. Time-of-tenability can be understood by analyzing the entire system with all components working together. To develop a time-of-tenability final curve, the project must develop:

1. A fire heat release curve as a function of time.
2. A design evacuation (egress) curve as a function of time.
3. A design systems response curve as a function of time.

1. The development of fire or a fire heat release curve is a function of:
   - Maximum FHRR,
   - Fire growth rate (quadratic curve for either super fast, fast, medium, or slow fire growth rate), and
   - Fire decay rate.
2. The egress timeline depends greatly on human behavior. For design purposes, there is a need to:
   - Assume that people will realize the danger, be notified to evacuate, make the right decision on the direction for evacuation, and go to the point of safety.
   - It is necessary to add times for detecting and alerting, reaction and leaving the vehicles, and walking to a safe place, to know if people can escape the fire safely.

   Spacing between emergency exits shall be justified by calculations. It is impossible to take fire and smoke under control immediately; therefore, for several minutes, fire and smoke will be driven by natural factors. This is the most important time for evacuation. The sooner smoke and fire are under control, the sooner there will be a tenable environment for evacuation. The distance that people can safely travel to an exit depends on the fire development and system activation. The primary role in system activation is fire detection. Thus, spacing between cross passages will largely depend on the fire-detection system.
3. Equipment activation time consists of the following phases for supervised tunnels:
   - Fire-detection time
   - Fire alarm and operator reaction time
   - Time to bring the first group of fans to full speed
   - Time to activate the fixed fire suppression system if desired
   - Achieve a full operational mode for ventilation system.

   For unmanned tunnels, the system is usually designed to be fully automatic or operated by the local fire department.

Based on fire development, emergency egress, and equipment activation timeline, it is possible to create a combined heat–egress system activation time curve. This curve allows for the analysis of the design HRR at every evacuation and system activation phase and aids in making the correct decisions.

A tenability map shows all time steps and the resulting impact on casualties and tunnel structure. It allows one to predict for how long the environment will be tenable in the tunnel and helps to decide what needs to be done to achieve fire life safety goals.

CHAPTER TWELVE

FIXED FIRE SUPPRESSION AND ITS IMPACT ON DESIGN FIRE SIZE

BACKGROUND

PIARC, NFPA, and several European countries are rethinking fixed fire suppression application for tunnels. Before the Alpine tunnel fire disasters, Japan and Australia were the only two countries to require and use sprinkler systems in road tunnels. It is noted that sprinklers were installed in several other tunnels around the world, including the United States. However, those installations were driven by specific requirements and jurisdictions (e.g., Seattle 1952).

Based on the literature review, all Japanese class 'AA' road tunnels are required to have sprinkler systems. (Class 'AA' are tunnels with traffic density of more than 40,000 vehicles per day with a length of more than 1 km or 3,280 ft.) Starting in 1963, a number of full-scale tunnel fire tests have been carried out in Japan. It was concluded that sprinklers are able to reduce fire size and temperature and prevent fire from spreading. In Japan, sprinklers have been used in two or three tunnel fire incidents per year. It shall be noted that the Japanese approach is to activate sprinklers with a 3-min delay. This approach differs from Australia, where sprinklers are activated immediately (it takes 30 s for the deluge system to activate).

Lessons from the Burnley Tunnel fire in Australia, where a major disaster was successfully averted by a brand new successfully working safety system, are currently being studied (*69*). In March 23, 2007, the fire in the Melbourne City Link Burnley Tunnel started with a road traffic accident involving four cars and three HGVs. The pile-up of trucks and cars inside the 3.4-km (2.1-mi) long Burnley Tunnel that killed three people burst into a wall of fire that reached temperatures of more than 1,000°C (1,832°F). However, further casualties were avoided. Although, according to the *Sydney Morning Herald* (*70*) some witnesses reported that they had not seen any sprinkler or safety system in operation, Acting Metropolitan Dire Brigade Chief Officer Keith Adamson said that both sprinkler and smoke extraction systems made it much easier to find the source of the fire. Hundreds of motorists were immediately advised to leave their cars with their keys in the ignition and evacuate the tunnel. Most took the emergency exits, which lead to separate pedestrian tunnels, whereas some took the riskiest route by walking back to the tunnel entrance. As a consequence, the Burnley Tunnel, which opened in late December 2000, is now widely regarded as an example of a modern safety model.

Despite a potentially huge fire and the presence of more than 400 people in the tunnel, only three people died from the traffic accident and none from the subsequent fire. The Burnley Tunnel incident demonstrates that fixed fire fighting systems are effective in protecting tunnel infrastructure and delivering human safety (*71*).

Presently, there are several ongoing discussions of the benefits of sprinklers. However, there were also some past lessons learned, which are reviewed here.

For example, as mentioned earlier, the Ofenegg Tunnel tests (1965) included a 500 L (132 gal) sprinkler test, sprinkler droplets initially evaporated into a high-temperature steam cloud, which caused more damage than the nonsprinklered fires. The open fire was apparently soon extinguished, but was accompanied by a strong odor of gasoline at the portal. The fire then reignited after 17 min (status of sprinkler flow unstated) with pronounced, but nonexplosive, wave-front propagation. However, the ultimate minimum survival distance for an upright subject was judged closer than for the nonsprinkled fires.

As noted in the Ofenegg Tunnel test report, during the 1,000 L (264 gal) gasoline burn tests the sprinklers were immediately activated after ignition. The sprinklers reduced the maximum arch temperature significantly. However, the steam apparently pushed burning gases and gasoline vapors into adjacent tunnel sections, where they continued to burn. The fire was apparently extinguished after 10 min, but the tunnel filled with gasoline vapors, which exploded in the nineteenth minute, causing extensive damage to the test setups and injuring three technicians. A lesson learned is that once the sprinkler system is activated, it is not to be turned off until the fire source is completely extinguished and determined safe.

A delay in activation produces huge volumes of high temperature steam, which can be as dangerous as the combustion products. If all ignition sources cannot be extinguished and the site uniformly cooled below a safe temperature, the fire will reignite, perhaps explosively, when the sprinklers are shut off. Meanwhile, unburned vapors are propelled around the tunnel and ventilation ducts, which can cause another significant hazard to those safely away from the fire, even after the fire is extinguished.

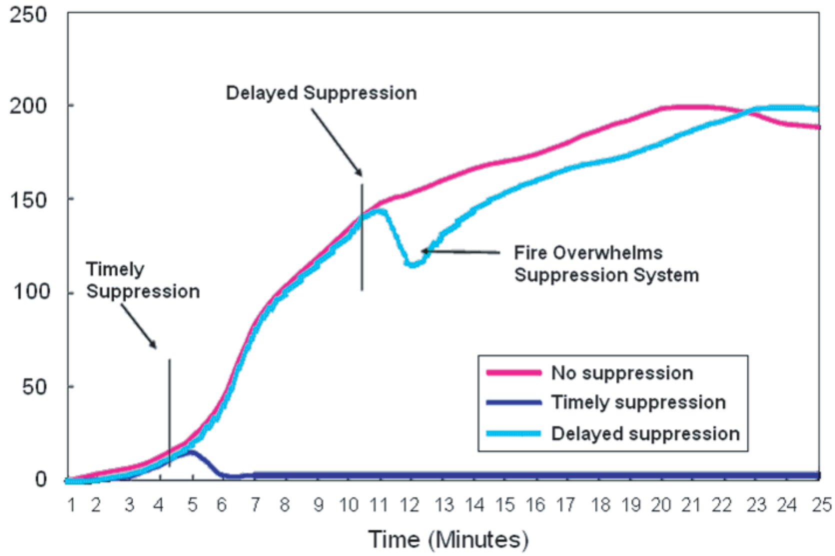

FIGURE 34 Schematic effect of suppression on heat release rate (*71*).

Figure 34 schematically shows the effect of suppression on HRR. With timely activation of a suppression system, the HRR is reduced. With delayed activation, the fire becomes overwhelming and the suppression system is not 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. It is essential that the detection system be capable of detecting a small fire (in the order of 1–5 MW). If this 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 (*72*).

Although a few automatic sprinkler systems have been installed in tunnels, most systems are deluge systems. A deluge system has a network of open nozzles at the roof of the tunnel, divided into zones, typically of 30 m (100 ft) based on the length of a HGV. When there is a fire, a valve is opened in the zone above the fire and in the zones on either side. Water is sprayed from all the nozzles in the activated zones.

Deluge systems have been selected over automatic sprinkler systems as a result of two concerns. First, the ventilation system in a tunnel could spread heat initially to sprinklers that are not above the fire. Second, a tunnel fire could rapidly develop a considerable amount of heat over a large area so that too many sprinklers would open, overwhelming the water supply. In 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 millimeters//minute. Droplets from water spray systems are generally larger than 1 mm (0.04 in.) in diameter.

Meanwhile, water mist systems use higher pressures, in some cases more than 100 bar (1450.4 psi), and discharge much finer droplets, 99% of which have a diameter less than 1 mm (0.04 in.). Nozzles with very small orifices are used to create the mist. The smaller droplets are drawn into the fire by its own ventilation and easily evaporate owing 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, saving on costs. However, to protect the small nozzle orifices higher quality materials, such as stainless steel, are required, which add to the costs.

Research projects are investigating to what extent an active fire protection system can limit the maximum HRR and whether an active fire protection system combined with ventilation offers equal or better life safety. The projects are also investigating how to specify design or performance test criteria for tunnel active fire protection systems. Today, more than 100 tunnels are equipped with an active fire protection system. Fixed fire suppression systems have been successfully used for more than 40 years in Japan's congested urban road tunnels and, more recently, in all of Australia's congested urban tunnels.

Road tunnel deluge systems require substantial amounts of water, which can have a significant impact on the storage, delivery, and drainage systems (although water mist systems require less water per zone). One study came to the conclusion that, although some minimum water application rates would achieve a certain objective, a marginally higher rate would not necessarily improve the situation (*51*).

Japan and Australia each have their own specified water application rates to use for road tunnel fixed fire suppression system design, which are 6 mm/min (0.15 gpm/ft^2) and 10 mm/min (0.25 gpm/ft^2), respectively. In full-scale tunnel sprinkler tests conducted in Europe (2nd Benelux), a water application rate of 14 mm/min (0.35 gpm/ft^2) has been tested. These values have been added to Figure 35 to demonstrate the significant variation in prescribed water application rates for which little research has been done to compare their effectiveness when applied under similar conditions.

Fire point theory shows that there are optimum rates of water application that can control a fire and are significantly less than the rates generally prescribed. Furthermore, this theory suggests that there are minimum water application rates that can reduce the heat flux below certain critical limits required to sustain combustion and, once these limits are reached, more water offers little or no benefit. The results of the comparative analyses suggest that water application rates as low as 2 mm/min (0.05 gpm/ft^2) can offer some benefits by cooling exposed surfaces and assisting in limiting the spread of fire from the initiating point (see Figure 35).

Although the conclusions are interesting, they need to be further evaluated by answering these questions:

- Does the water requirement depend on the design HRR? Typically, the higher the FHRR, the more the water evaporates.
- Does the water requirement depend on fire size at the time of fixed fire suppression system activation? It appears that the earlier the system will be activated, the lower the FHRR will be and the less water may be required. Some previous works have already demonstrated that late fixed fire suppression system activation resulted in an inability to take the fire under control, which caused the FHRR to continue to increase.
- Does water requirement depend on ventilation and longitudinal air velocity? Ventilation may have a dual effect. Ventilation may blow away or exhaust water particles from the fire site. Ventilation may also increase the speed of evaporation. The blow away effect may result in the need for activation of additional fire zones. The intense evaporation needs additional studies.

The following conclusions were drawn in the UPTUN project on the basis of the fire tests with the fire mitigation systems:

- Validation of the performance of fire safety equipment, such as water spraying systems, requires full-scale fire testing and cannot be trusted from model simulations.
- The efficiency of the water mist systems was satisfactory.
- However, the efficiency was strongly dependent on the size of the fire (or heat generation rate), nozzle type, location, and the water discharge rates.
- For the smallest fires (less than or equal to 5 MW or 17 MBtu/hr) the mitigation effect was minor.
- The best results were achieved for the largest fires (i.e., a HRR at or above 20 MW or 68 MBtu/hr). The maximum reduction of the HRR was 80%.
- A rapid reduction of the temperatures downstream of the fire was noticed after activation of the suppression system. The efficiency of both water mist systems was satisfactory with respect to heat stresses as well as the toxicity of the fire effluents on human beings.
- The visibility was not improved downstream of the fire during the first minutes after activation of the suppression systems. However, the visibility was generally increased as the fire size and the HRR were reduced during fire suppression.
- The problem of backlayering (i.e., smoke spread upstream of the fire) and the visibility upstream were also significantly improved after activation of the water mist systems.

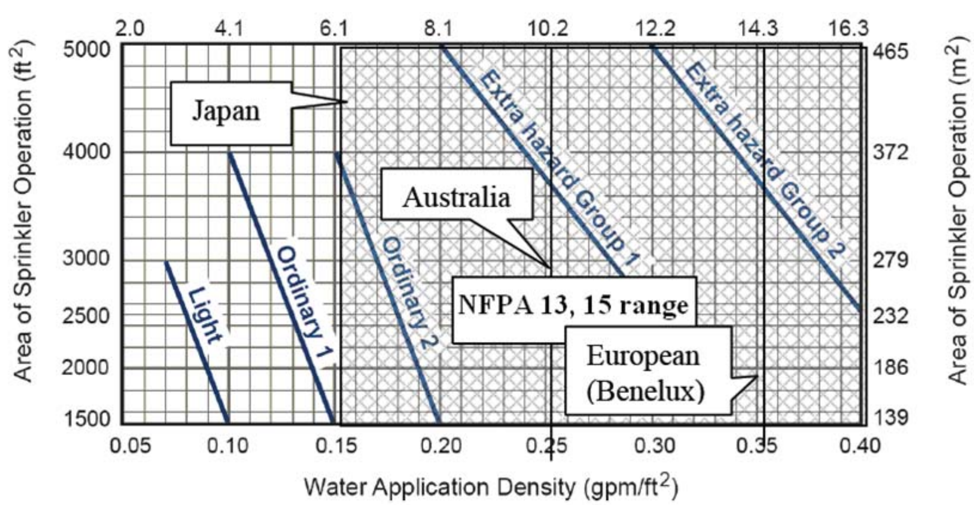

FIGURE 35 NFPA 13, NFPA 15, and other International Water Application Rates (*51*).

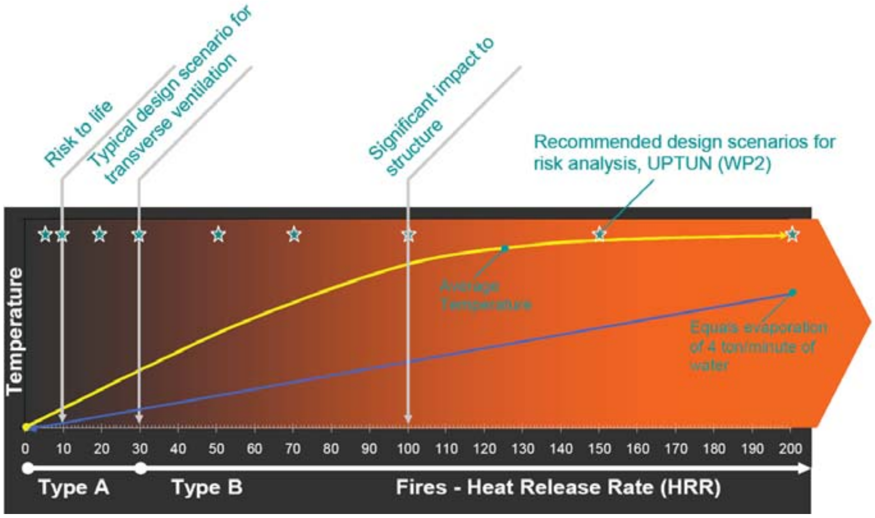

FIGURE 36 UPTUN Fire Heat Release—Temperature curve for classifications of ventilation and fixed fire suppression systems (*73*).

- High pressure water mist systems are using less water and suppress the fire to a higher degree in the gas phase of the flames. However, for the low pressure systems, the fire extinguishing effect is mainly cooling of the fuel surfaces.

Figure 36 shows Type A fires where mitigation action is provided, whereas Type B often represents fires out of control and may provide significant heat exposure to the structure.

Type A fires are assumed to be significantly less severe than Type B fires, which may result in unbearable conditions for humans and significant thermal exposure to constructions. Small fires, Type A, are often limited to the first object burning and can be ranked by the HRR measured in megawatts or 1,000 Btu/hr, although more severe fires, after significant flame spread, can also be measured in terms of time–temperature curves.

For the UPTUN fire mitigation test program, the main focus has been on Type A fires to protect human beings, to avoid flame spread, and to provide conditions for unhindered escape and rescue. Type A fires can be considered as fires with a HRR of up to 30 MW (102 MBtu/hr), whereas higher HRR can be considered as Type B fires.

To operate effectively, the fixed fire suppression system has to be properly maintained. The operator must be able to activate it correctly, and it must survive the events that have resulted in the incident requiring its activation.

Automatic activation of the sprinklers by active detectors may need to be delayed because even a light spray could startle unaware drivers and make the roadway slippery. Water squirting from the ceiling of a subaqueous tunnel would suggest tunnel failure and can induce panic in motorists.

Accidental activation of the system with the cause unknown, which happened in Boston, is not acceptable (see Figure 37). A malfunctioning activation of the sprinkler system drenched the tunnel under City Square in Charlestown, converting the 1,100-ft (335.3-m)-long tunnel into a temporary car wash. The activation was inadvertent and the source of the activation unconfirmed. The malfunction activation forced State Police to close the three main ramps that lead traffic from Storrow Drive, Interstate 93 north, and Rutherford Avenue into the tunnel.

It is recognized that active fire protection systems can limit the size and growth of a fire and prevent the fire from spreading. It is also recognized that active fire protection systems will limit damage to the tunnel in the event of a fire, so that even a fire involving several HGVs will not close the tunnel for long. It could also protect tunnel lining, possibly reducing the amount of passive structural fire protection and providing significant construction savings.

At the control level there are a range of opportunities to fully integrate such systems with the ventilation, operate them

FIGURE 37 Accidental activation of the sprinkler fire suppression system in Boston CANA (Central Artery North Area Tunnel) for 45 min on May 15, 2005, at 2 p.m. (*54*).

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 will require different approaches.

One important lesson learned from the Ofenegg and other tunnel tests is that it is dangerous to turn the fire suppression system off while surfaces are still hot and fuel vapors are present, because they can ignite and cause an explosion. A well-thought out operation of the fixed fire suppression system is important because fire sizes can be very large.

For an active fire protection system to be effective it is essential that fires are quickly and accurately detected. Sprinkler systems are to be designed to prevent a fire from reaching its peak; however, the droplets will be affected by ventilation. Longitudinal airflow must be selected to ensure an appropriate droplet spread and mass flow performance for given water pressures. No doubt ventilation system performance is also affected by sprinkler operation. However, the main idea is to get a well-designed system with a reliable quick fire-detection system to start these systems before the fire gets too large.

For an effective deluge operation, activation must be rapid and accurate. If discharged in this way, fire growth rates are likely controlled, the risk of rapid fire spread minimized, and, thereby, toxic gas and smoke generation volumes contained.

The undesirable consequences of its activation, such as smoke de-stratification, increased humidity, and decreased visibility, are hopefully outweighed by their other positive outcomes of fire growth rate control, containment of fire spread, and reduced temperatures.

The Runehamar tests brought up the question: Is it possible to manage a 200 MW (682 MBtu/hr) fire? A fire suppression industry offers to control the fire size, reducing the maximum HRR by applying a fixed fire suppression system. Once a fire is early detected by a reliable fire-detection system, the fire protection system could be activated within several minutes, taking the fire in the order of about 10 MW (34 MBtu/hr) and under control, or suppress a small fire. However, the question is what this will do for the tunnel safety (Table 33).

With the longitudinal ventilation system, it appears reasonable to activate both systems simultaneously. As a result, the wet fixed fire suppression system will initially start before the longitudinal ventilation reaches full speed. Note that it takes 30 s to discharge water if it is a wet system, whereas it takes 3 min to achieve a full operational ventilation mode. This

TABLE 33
IMPACT OF A FIXED FIRE SUPPRESSION SYSTEM (FFSS) ON TUNNEL FIRE SAFETY

Advantages of FFSS	Challenges of FFSS
General	
A sprinkler is designed to react at an early stage of the fire. Takes fire under control, not allowing it to further grow, or grow slowly, or extinguishes a small fire before the fire department arrives.	Possible loss of visibility (reduced visibility) especially at an early stage when people evacuate. When the sprinkler system is activated on an already large fire, 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 to protect the tunnel structures.
Reaching the fire: help rescue team and firefighters to reach the fire source.	Creates slippery environment when water applied. May create panic when it malfunctions with an accidental water release. If a system (a normal wet sprinkler) is activated by a defect such as breaking of the glass, water will be sprinklered into a tunnel with a possibility of causing an accident.
Transverse ventilation based on smoke extraction (*including single-point extraction*)	
Reduced fire size, see also general	Destroys stratification of hot air, which makes ceiling extraction inefficient and evacuation difficult.
Reduced fire duration	Increases mass of air/water mixture to move, results in increased vent rate for sidewall extraction system.
Longitudinal ventilation—unidirectional tunnel with manageable traffic	
Reduced fire size may result in reduced ventilation rate	Increases mass of air/water mixture to move—increases vent rate
Cools environment and protects fan units from high temperature	Overcomes water curtains created by the FFSS—increases vent rate
See general	Blows the FFS substances away from the fire—increases number of FFS zones for activation.
Longitudinal ventilation—unidirectional tunnel with unmanageable traffic or bidirectional tunnel	
Protects tunnel structure	Destroys stratification making evacuation difficult (maybe impossible) to both sides of the fire once the FFSS is activated. Traffic control for low traffic tunnels is imperative.

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.

With the transverse ventilation system using ceiling exhaust, the sequence of activations may differ. The primary purpose of the fire life safety system is to save lives and allow for safe evacuation. Destruction of the smoke layer, worsening of visibility, and potential generation of hot steam, need to be considered. The Japanese approach for the transverse system may be reasonable, which allows for a minimum of a 3-min delay before the 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. This confirms the need for an integrated approach to all fire life safety systems (*2*).

There are a number of questions that need further study:

1. NFPA 502 and other standards allow for a maximum air velocity in a tunnel of 12 m/s (2,200 fpm). 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 be that high. What will such velocities do to a fixed fire suppression system's performance?
2. Once a fixed fire suppression system is activated, it will create a water curtain in the tunnel for longitudinal air velocity. The air velocity will be reduced and could be less than critical for the sprinkler controlled fire HRR. Will smoke be under control or does the ventilation system performance need to be increased?
3. If a sprinkler is activated early enough, can ventilation be reduced or eliminated and what will be the impact on smoke production?
4. A fixed fire suppression system will increase humidity in the tunnel. How will this humidity affect the ventilation and fan's performance?
5. Other questions are related to fire detection and the operator's control of the situation, low visibility, hazardous slippery conditions, system activation malfunction concerns, and optimum systems activation time.

Critical factors such as droplet size distribution and trajectory modeling of droplets through a range of longitudinal velocities are essential for CFD modeling.

NFPA 502 recognizes the benefits of the fixed fire suppression system for road tunnels, but is concerned with the available fire-detection technology, with the further visibility reduction, and with the impact of the fixed fire suppression system on the effectiveness of tunnel ventilation.

Annex E (the explanatory material) of NFPA 502 (2008 edition) notes that the major concerns expressed in the past by tunnel designers, engineers, and authorities worldwide regarding the use and effectiveness of water-based fixed firefighting systems in road tunnels, along with the current assessment of those issues have been revisited as follows:

1. *Fires in road tunnels usually occur inside vehicles or inside passenger or engine compartments designed to be waterproof from above; therefore, water-based fixed firefighting systems would not have an extinguishing effect.*

   It is now recognized that the purpose of a water-based fixed firefighting system is not to extinguish the fire but to prevent fire spread to other vehicles so that the fire does not grow to a size that cannot be attacked by the fire service.
2. *If any delay occurs between ignition and the water-based fixed firefighting system activation, a thin water spray on a very hot fire could produce large quantities of superheated steam without materially suppressing the fire.*

   Fire tests have shown this not to be a valid concern. A properly designed water-based fixed firefighting system suppresses the fire and cools the tunnel environment. Because a HGV fire needs only 10 min to exceed 100 MW (341 MBtu/hr) and 1200°C (2192°F), which are fatal conditions, it is important to operate the fixed firefighting system as soon as possible.
3. *Tunnels are long and narrow, often sloped laterally and longitudinally, vigorously ventilated, and never subdivided: therefore, heat normally will not be localized over a fire.*

   Advances in fire-detection technology have made it possible to pinpoint the location of a fire in a tunnel with sufficient accuracy to operate a zoned water-based fixed firefighting system.
4. *Because of the stratification of the hot gas plume along the tunnel ceiling, a number of the activated fixed fire suppression systems would not, in all probability, be located over the fire. A large number of the activated water-based fixed firefighting systems would be located away from the fire scene, producing a cooling effect that would tend to draw the stratified layer of smoke down toward the roadway level, thus impeding rescue and firefighting efforts.*

   Independent laboratories have commented that they do not observe smoke stratification. Any activated water-based fixed firefighting system not over the fire would cool the tunnel to help rescue services to intervene. Zoned systems are released by a detection system that is accurate even with forced ventilation.
5. *Water spraying from the ceiling of a subaqueous tunnel could suggest tunnel failure and induce panic in motorists.*

   This theoretical concern was not borne out in practice. In the event of a fire, motorists are likely to recognize water spraying from nozzles as a fire safety measure. Behavioral studies have shown that most people do not panic in a fire, even when they are unable to see.

6. *The use of water-based fixed firefighting systems could cause the delamination of the smoke layer and induce turbulence and mixing of the air and smoke, thus further threatening the safety of persons in the tunnel.*

   This has been shown not to be a valid concern. Fire tests have demonstrated that smoke does not usually form a layer at the top of the tunnel but quickly fills the cross section. Normal air movement in the tunnel accelerates this process. A water-based fixed firefighting system reduces temperatures and the risk of fire spread to other vehicles.

7. *Testing of a water-based fixed firefighting system on a periodic basis to determine its state of readiness is impractical and costly.*

   A full discharge test is normally performed only at system commissioning. During routine testing, the system can be configured to discharge flow to the drainage system.

SUMMARY

PIARC, NFPA, and several European countries are rethinking their position on fixed fire suppression system application for their tunnels. It is recognized that sprinklers are able to reduce fire size and temperature and prevent fire from spreading. In addition, it is recognized that timely activation of active fire protection systems will limit damage to the tunnel in the event of a fire. However, there were also some earlier lessons, which are to be reviewed when making a decision:

- Once the sprinkler system is activated, it shall not be turned off until a fire source is completely extinguished and the tunnel determined to be safe.
- With timely activation of a suppression system, the HRR is reduced. With delayed activation fire overwhelms and the suppression system may not be effective. Extended delay with a fixed fire suppression system may result in its inability to control fire, in structural damages, and possible explosions. A reliable automatic fire-detection system is essential.
- It is essential that the detection system is capable of detecting a small fire (in the order of 1–5 MW)
- Accidental activation of the sprinkler system is unacceptable.

Today, more than 100 tunnels worldwide are equipped with an active fire protection system. Although a few automatic sprinkler systems have been installed in tunnels, most systems are deluge systems. Water mist systems may require less water per zone. Storage tanks, pumps, and pipes can be smaller, saving on costs. However, to protect the small nozzle orifices higher-quality materials, such as stainless steel, are required, which add to the costs.

The type of ventilation system influences the type of sprinkler system and the sprinkler system design impacts the ventilation system performance. Some of the challenges faced with considering ventilation and fixed fire suppression systems in the tunnel are:

- Selection of the type of fixed fire suppression system depends on the type of tunnel ventilation system.
- Wet fixed fire suppression systems can be activated before ventilation and can control fire growth rate, fire size, and the overall smoke production rate at an early stage of fire development.
- Activation time of a fixed fire suppression system may differ depending on the type of ventilation.
- For longitudinal ventilation, the sprinkler zones may need to be switched or additional zones may be required once ventilation mode is in full speed.
- With transverse ventilation, a short system activation delay may need to be considered.
- Delay with the fixed fire suppression system activation will require additional water supply because of the larger fire size at the time of activation.
- Extended delay with a fixed fire suppression system may result in its inability to control fire, in structural damages, and a possible explosion. A reliable automatic fire-detection system is essential.

The undesirable consequences of fixed fire suppression system activation, such as smoke destratification, increased humidity, and decreased visibility, are hopefully outweighed by its other positive outcomes of fire growth rate control, containment of fire spread, and reduced temperatures.

The questions that need additional investigation are whether the fixed fire suppression system can replace other tunnel fire life safety systems, such as ventilation and passive protection systems, or whether the size and requirements for such systems can be reduced.

CHAPTER THIRTEEN

EFFECTS OF VARIOUS VENTILATION CONDITIONS, TUNNEL GEOMETRY, AND STRUCTURAL AND NONSTRUCTURAL TUNNEL COMPONENTS ON DESIGN FIRE CHARACTERISTICS—LITERATURE REVIEW

INFLUENCE OF VENTILATION ON FIRE HEAT RELEASE RATE

Prior publications reported that mechanically ventilating a fire could result in a more rapid fire development (*35*). The Second Benelux Tunnel fire test addressed the influence of ventilation on the FHRR (*74*). The fire development rate, with a ventilation air velocity of 4 to 6 m/s (787 to 1,181 fpm), appeared to be two times faster than development without ventilation. The peak heat output was about 1.5 times higher. The increase in HRR and fire growth rate, a result of 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. Theoretically, a fire on densely packed wood cribs may be locally underventilated; however, in forced ventilation flow, the transport of oxygen to the underventilated region enhances the combustion rate.

In most road tunnels, such as the Benelux Tunnel (*74*), there is a large amount of oxygen already available and the availability of oxygen is not increased by the ventilation. At the same time, the ventilation has a cooling effect on the fire environment, whereby the heat can be easily let out to the environment.

Ventilation has an influence on the fire development that does not always conform to expectations (*75*):

- Owing to increased ventilation, the fire development for a car can be slowed if the fire is ignited at the front of the car. This is in contrast to the accepted view of supposed accelerated development resulting from ventilation.
- The influence of increased ventilation on the observed fire behavior depends on the ignition location. Note that 95% of fires begin in the engine compartment (i.e., at the front).
- Under the influence of a high-ventilation velocity, the fire development accelerates for a covered load at a rate 2 to 3 times faster, and not by a factor 20 as predicted by some authors. The fire size was 20% to 50% higher as a result of a high-ventilation speed.

The results from model fire tests indicated that if the wood cribs are densely packed the increase in peak HRR by ventilation can be up to a factor of 1.5. If not densely packed, there was little change in the peak HRRs. However, the Runehamar fire tests showed no significant HRR changes resulting from ventilation [up to air velocities of 2 to 2.5 m/s (394 to 492 fpm)]. Earlier discussions about a stronger dependence were not confirmed by the Runehamar experiments.

Ventilation is applied during a fire to keep escape routes free from smoke and to assist the fire department and others in reaching the accident site. In most cases, mechanical ventilation will lead the fire to burn fully. Thus, the total duration of the fire will be limited and the structure will not be subjected to a high thermal load concentration.

It is understood that there could be a negative effect on ventilation as forced ventilation may cause significant 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.

As reported, when a powerful ventilation system is suddenly activated during an underventilated fire situation, the effects may be dramatic; the flames may suddenly increase in size and length and the fire may easily spread forward because of the preheated vehicles downstream of the fire. However, this phenomenon cannot be defined as flashover. This situation may become very hazardous for firefighters and those who are still trapped inside the tunnel. Starting a ventilation system when the fire has been going for some time in a tunnel with high vehicle density is always very risky. However, as ventilation cannot immediately reach its full operating mode, the risk is not that significant.

Literature observations were made from the Benelux and Runehamar fire tests on the influence of ventilation rate on fire growth rate and are presented in Table 34.

Tests have indicated that it may be that the fastest fire growth occurs at about 3 m/s airflow velocity. 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 (*72*).

TABLE 34
INFLUENCE OF VENTILATION RATE ON FIRE GROWTH RATE

Ventilation Rate	Growth Rate
Less than 1 m/s	About 5 MW/min
About 3 m/s	About 15 MW/min
About 6 m/s	About 10 MW/min

Source: Ko and Hadjisophocleous (*31*).

INFLUENCE OF TUNNEL GEOMETRY ON FIRE HEAT RELEASE RATE

A tunnel is a confined space and presents one of the "worst case" geometrical shapes for fire development. The low ceiling and small cross section provide conditions that are conducive to high thermal loads to the tunnel structure.

The Runehamar fire tests reached 200 MW (682 MBtu/hr) using mockups of HGVs with high combustible loads in a tunnel with a relatively small cross-section area and under longitudinal airflow. These test results may not be directly applied to a tunnel with conventional cross-sections dimensions. Beard and Carvel (*35*) have developed the approach to evaluate the impact of geometry on the FHRR. The research showed that for a given combustible load the FHRR of a fire will vary depending primarily on the relative width of the tunnel and the fire source (*35*). They concluded that fires that are small relative to the size of a tunnel will not be significantly influenced by the tunnel geometry. Fires up to about half of the width of a tunnel will be enhanced by the tunnel geometry, whereas fires with dimensions close to the width of the tunnel will be reduced.

When compared, fires within narrow tunnels will generate a larger HRR for the same fuel load than within wider tunnels, assuming sufficient air is available for burning in both cases. (Tunnel height in those studies was much less a factor.)

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

$$HRR_{\text{tunnel}} = \left(B_{\text{tunnel}} / B_{\text{Runehamar}}\right) HRR_{\text{Runehamar}} \qquad (28)$$

where:

$$B = 24\left(W_{\text{fire}} / W_{\text{tunnel}}\right)^3 + 1 \qquad (29)$$

(The equation is valid for "enhancing regime" as identified by Beard and Carvel. The relationship between tunnel geometry and fire size has yet to be established in the "diminishing regime.")

This equation allows one to estimate the design FHRR against the values obtained in the Runehamar tests, considering that $Q_{\text{Runehamar}} = 203$; $W_{\text{fireR}} = 2.9$ m $W_{\text{tunnelR}} = 7.3$ m, or in any other tests. Estimates show that for a 15 m (49.2 ft) tunnel, the design FHRR is about 100 MW (341 MBtu/hr). This methodology was verified by the observation of numerous large-scale tests and by CFD results (*75*).

The slope of the tunnel has an important influence on the dispersion of the flue gases. In general it can be said that owing 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 FHRR and fire growth rate, as was discussed in the previous chapter.

INFLUENCE OF STRUCTURAL AND NONSTRUCTURAL COMPONENTS ON FIRE HEAT RELEASE RATE

A tunnel will have a "fixed" and a "variable" fire load. The fire load resulting from fixed tunnel components, such as wall linings, and contents, such as cables, track, power supply network, signaling system, lighting system, and radio transmission equipment, can be assessed based on a statistical survey of typical tunnels. In a road tunnel, the variable fire load consists of road vehicles and is more difficult to define because the density of the vehicles present in the tunnel is variable and a tunnel fire would not be expected to involve all of the vehicles in the tunnel.

In a tunnel fire, it is unlikely that the fire will involve all of the available fuel. In the growth stages, road vehicles are of most interest. Later, elements of the tunnel, such as linings, might become involved.

The size of the initiating fire and type of fuel is important because a relatively small fire source may not be capable of igniting the material contents or the compartment lining materials of the vehicle. Somewhat larger sources may be capable of igniting certain material contents, but not lead to flashover. Larger or critical ignition sources result in flashover within the vehicle.

Increasing the size of the initiating fire will increase the heat flux produced by the initiating fires. Increasing the HRR of the fire may also increase the flame height, exposing larger areas of material to high heat fluxes.

Materials exposed to higher levels of heat will ignite more readily, release more heat, and potentially lead to the greater spread of flame. The location of the initiating fire will also affect the heat fluxes produced by the fire.

The tunnel structure generally consists of a concrete lining. The primary function of the tunnel lining is to bear the loads acting on the structure, especially in the event of fire. Different types of concrete are used in tunnels. Depending on the type of tunnel, generally normal strength or high strength concrete are used. Different kinds of concrete will react differently to fires. The goal is to have cost-effective, durable concrete that will have sustained load-bearing capacity during fire and eventually without structural damage.

Concrete tunnel structures can lose their load-bearing capacity through several failure mechanisms. The main mechanisms relevant for tunnel linings are (*65*):

- Bending
- Buckling
- Shear
- Spalling.

A loss of resistance against these mechanisms is caused by a loss of strength of both concrete and reinforcement. Buckling, shear, and spalling can also be the result of additional internal stresses that arise during a fire.

When concrete is heated, the temperature increase will result in a loss of (compressive and tensile) strength. Although this effect is dependent on the composition of the concrete, as in the particular type of aggregate material, the best way to prevent strength loss of the concrete is by reducing the heat penetration. This can be obtained by applying a heat-isolating layer on the concrete surface.

A realistic structural load can be determined by advanced nonlinear finite element simulations. For concrete construction, a main failure mechanism is spalling. When concrete is heated, spalling can lead to extensive damage to the construction. Therefore it is of vital importance to consider the risk of spalling. It is important to note that spalling of concrete is not directly dependent on the strength of the concrete, but more on compression, concrete mix design, permeability, and moisture in the concrete. Spalling is a highly relevant failure mechanism in concrete tunnel structures, which is driven by the temperature increase rate and thermal gradient over the structure than by temperature alone. As a result, a conservative upper bound for the fire curve cannot be obtained just by modification of the fire load. It includes other parameters as well, such as ventilation conditions and wall properties.

Spalling is an umbrella term covering different damage phenomena that may occur to a concrete structure during fire. These phenomena are caused by different mechanisms:

- Pore pressure rises as a result of evaporating water when the temperature rises.
- Compression of the heated surface resulting from a thermal gradient in the cross section.
- Internal cracking resulting from differences in thermal expansion between aggregate and cement paste.
- Cracking resulting from differences in thermal expansion/deformation between concrete and reinforcement bars.
- Strength loss owing to chemical transitions during heating.

In different combinations of these mechanisms, possible spalling phenomena include:

- Violent spalling
- Progressive gradual spalling
- Corner spalling
- Explosive spalling
- Post-cooling spalling.

It is important to understand the post-cooling spalling mechanism because it leads to a better understanding of a fixed fire suppression system application for structural fire protection.

Post-cooling spalling occurs after the fire is out, after cooling down, or maybe even *during extinguishing.* This type of spalling was observed with concrete types containing calcareous aggregate. An explanation is the rehydration of CaO to $Ca(OH)_2$ after cooling, with an expansion of more than 40%. This occurs after cooling down, when moisture is again present on the concrete surface (*65*).

The expansions resulting from rehydration cause severe internal cracking on the meso-level and, thus, complete strength loss of the concrete. Pieces of concrete will keep falling as long as there is water to rehydrate the CaO in the dehydrated zone.

It appears that the application of a fixed fire suppression system on the very early stage of a fire development can actually help cool down the fire and surface and protect the structure, whereas a delay can initiate a post-cooling spalling. This leads to an understanding of the importance of a reliable fire-detection system and activation of the fixed fire suppression system at the very early stage of fire development to cool down the tunnel's walls. By limiting the development of a fire its duration can be limited, resulting in the tunnel structure enduring less harsh conditions.

The question that needs additional studies is: it is well known that protecting tunnel structures with heat-resistant coatings or materials will reject the heat generated by the fire back into the tunnel environment. In other words, it will not allow for heat to dissipate through the walls. This could potentially increase the tunnel heat in the range of 30% or more. This requires additional studies to answer the question: What is happening to the tunnel environment and tunnel heat by protecting the tunnel walls? Will the fire life safety systems, including tunnel fans withstand that additional heat component?

The cooling down of the tunnel's walls could be accomplished by using sprinklers on a very early stage of fire development. By limiting the development of the fire the duration of the fire can be limited and the structure of the tunnel will be subjected to less harsh conditions.

SUMMARY

Ventilation has an influence on the fire development:

- Owing to increased ventilation, the fire development for a car can be slowed if the fire is ignited at the front

of the car, or can increase if the fire is ignited in the back of the car.
- The influence of increased ventilation on the observed fire behavior depends on the ignition location.
- Under the influence of a high-ventilation velocity, the fire development accelerates for a covered load at a rate 2 to 3 times faster. The fire size is expected to be 20% to 50% higher owing to a high-ventilation speed.
- If the wood cribs are densely packed, the increase in peak HRR by ventilation can be up to a factor of 1.5.
- No significant HRR changes owing to ventilation [up to air velocities of 2 to 2.5 m/s (394 to 492 fpm)].
- In most cases, mechanical ventilation will lead the fire to burn fully. Thus, the total duration of the fire will be limited and the structure will not be subjected to a high thermal load concentration.
- There could be a negative effect of ventilation because forced ventilation may cause significant 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.
- The fastest fire growth occurs at about 3 m/s airflow velocities. Both higher and lower ventilation rates may result in slower growth fires.

Tunnel geometry may have a significant impact on fire HRR:

- For a given combustible load, the FHRR of a fire will vary depending primarily on the relative width of the tunnel and the fire source:
  - Fires that are small relative to the size of a tunnel will not be significantly influenced by the tunnel geometry;
  - Fires up to about one-half of the width of a tunnel will be enhanced by the tunnel geometry; and
  - Fires with dimensions close to the width of the tunnel will be reduced.
- When compared, fires within narrow tunnels will generate larger HRR for the same fuel load than within wider tunnels, assuming sufficient air is available for burning in both cases.
- The slope of the tunnel has an important influence on the dispersion of the flue gases. In general it can be said that owing to the chimney effect, the dispersion velocity of the flue gases increases with the increase in tunnel slope.

It is unlikely that the fire will immediately involve all of the available fuel. In the growth stages, road vehicles are of most interest. Later, elements of the tunnel, such as linings, might become involved.

- Materials exposed to higher levels of heat will ignite more readily, release more heat, and potentially lead to more flame spread.
- The best way to prevent strength loss of the concrete is by reducing the heat penetration.
- Spalling is a highly relevant failure mechanism in concrete tunnel structures, which is driven by the temperature increase rate and thermal gradient over the structure than by temperature alone.
- It is very important to understand the post-cooling spalling mechanism because it leads to a better understanding of a fixed fire suppression system application for structural fire protection.
- A fixed fire suppression system application on a very early stage of a fire development can actually help to cool down the fire and surface and protect the structure, whereas delay with its activation can initiate a post-cooling spalling.

EXAMPLE OF DESIGN FIRE SIZE ESTIMATE

Every tunnel is unique and this example is for illustration purposes only. Each project has to establish the design fire size accepted by the stakeholders and the Authority Having Jurisdiction.

Consider that a tunnel is twice the width of the Runehamar Tunnel and the designer is using the most conservative test result—the maximum FHRR from the HGV fire of 200 MW. This example illustrates the impact of tunnel geometry, tunnel exit design, reliable rapid fire detection, and benefits of fast activation of the fire suppression system capable of controlling the fire (Table 35).

Table 36 represents the resultant fire curve modified by the fixed fire suppression system rapid activation. Rapid fire detection, early start of self-rescue, and fast application of a sufficient fixed fire suppression system could reduce the design fire size 10 times or more. An insufficient fixed fire suppression system design will not control fire, which will keep growing. Proper fixed fire suppression system design will either keep the fire at the starting rate (10 MW in this example) or reduce the fire up to extinguishing. (In reality the process is more complicated and fire may keep growing for a short period of time after fixed fire suppression system activation, and then get reduced.) Early deactivation of the fixed fire suppression system may lead to explosion and unmanaged fire. This example is not applicable to the liquid fuel fires or alternative fuel vehicles fires.

TABLE 35
EXAMPLE OF DESIGN FIRE

	Design Fire Scenario for Self-rescue	Design Fire Scenario for Structural Protection	Design Fire Scenario for Central Mechanical Equipment Fire Rating
Maximum fire HRR for HGV with cargo similar to the Runehamar tests	200 MW (see "Full-Scale Tests" in chapter six)	200 MW; RWS curve (see "Time-temperature . . ." in chapter eleven) (1350ºC; 2462ºF)	200 MW
With geometry correction (no tunnel grade correction made)	100 MW (see example in "Influence of Tunnel Geometry . . ." in chapter thirteen)	100 MW RWS curve (see "Time–Temperature . . ." in chapter eleven) (1350ºC; 2462ºF)	100 MW
Consider self-evacuation to the nearest exit is 10 min	80 MW using ultra-fast fire growth curve (see "Combined Curve for Evacuation . . ." in chapter eleven)	No correction	No correction
Consider fast fire detection and sufficient wet FFSS system activation within 4 min before ventilation in full effect	10 MW (see revised fire curve due to rapid FFSS activation illustrated in Table 36)	10 MW, but with a faster temperature growth rate (additional structural protection may not be required. Computational analysis needed)	10 MW, but design temperature not less than 250ºC (482ºF, see chapter nine)
Correction for ventilation	N/A as FFSS is activated before ventilation.		
Correction for tunnel drainage	N/A as HGV was used in the example assuming no liquid fuel spillage.		

For illustration purposes only.
N/A = not available.

TABLE 36
EXAMPLE OF DESIGN FIRE CURVE

Self-Rescue	FLS Systems Activation
A. Make a decision to evacuate	1. Detection time
B. Disembark the bus	2. Operator reaction time (alarm)
C. Walk away from the fire-effected zone	3. FFSS activation
D. Reach cross passage	4. All fans activated
	5. Ventilation mode in full operation

For illustration purposes only.

CHAPTER FOURTEEN

CONCLUSIONS

Every tunnel is unique, which makes it very difficult to generalize design fires in road tunnels. On average, based on the survey results conducted for this effort, a fire in each U.S. tunnel occurs 1 or 2 times a year.

A number of tunnel fire safety projects, fire tests, and research work that have been initiated around the world in the last 10 years have brought to light a significant amount of information. This helps us to better understand tunnel fires and the safety means to prevent them and to protect tunnels. The most important documented projects are:

- FHWA Prevention of Tunnel Highway Fires
- TRB/NCHRP Making Transportation Tunnels Safe and Secure
- International Technology Scanning Program sponsored by FHWA and others
- UPTUN, European Project (EP)
- FIT (Fire in Tunnels), EP
- DARTS (Durable and Reliable Tunnel Structures), EP
- SafeT (a Thematic Network on Tunnels), EP
- Safe Tunnel, EP
- SIRTAKI, EP
- Virtual Fires, EP
- EuroTAP, EP
- SOLIT, EP
- L-surF, EP
- EGSISTES, EP.

Numerous fire tests were performed or analyzed as part of these projects. The most important are:

- The Memorial Tunnel Fire Tests (United States)
- Ofenegg tests (Switzerland)
- Zwenberg tests (Austria)
- PWRI tests (Japan)
- Repparfjord tests (Norway)
- Benelux tests (the Netherlands)
- Runehamar tests (the Netherlands)
- Other tests as part of UPTUN project.

The full-scale experiments generally provide interesting qualitative observations. For example, some opaque situations appear clearly as a combination of the heat release rate (HRR), the nature of the burning object (smoke density), and the longitudinal air velocity. The relatively low number of experiments does not lead to general conclusions. (An exception would be the Memorial Tunnel program because of the large number of tests.) These observations might be used as a reference for more specific research works using appropriate tools (small-scale or numerical models). Table 37 summarizes the benefits for the research, design, and operation of tests and models, with their advantages and disadvantages.

- The Memorial Tunnel Fire Ventilation test program produced much empirical data and information for future analysis. It was performed in a real tunnel with geometry similar to other road tunnels. However, this test was accomplished with fuel pans, which hindered an understanding of what fire size and fire growth would result from real major tunnel fire events. A number of European tests with real cars, buses, and trucks were performed in tunnels of smaller cross-sectional area. Extrapolation of that data to real tunnel geometry is to be done with care. Because of a lack of full-scale fire tests with real trucks and buses in a real geometry, confirmation of the results of the Runehamar tests is not possible.
- There are no regularity requirements in the United States for performing hot smoke tests or burning cars when commissioning new tunnels. The European experience allows for the verification of fire life safety systems designs, train designers, operators, and first responders.
- Small-scale tests and reduced-scale tests are in need of further development. These tests are less expensive and are needed for scientists and designers, because they allow for better understanding of the physics of the process and help verify the computer modeling. Such tests can be repeated in the design at any time and be used for visualization of the smoke behavior in the tunnel depending on the system's response.
- Computational fluid dynamics (CFD) software is considered as the design tool of choice for obtaining an optimum design. However, it requires in-depth knowledge of physical processes and numerical models, and preferably experience in testing from the numerical modeler. The strengths and weaknesses of each program are to be investigated beforehand, while validation of the results against experimental data or another equivalent program is encouraged. Good experimental data are required. New small- or large-scale experiments are to be undertaken with the priority objective of validating and calibrating physical models. It may include the understanding of flow generated by fire as well as measurements of some physical smoke properties, which are critical for models

TABLE 37
FIRE TESTS AND FIRE MODELING FOR RESEARCHES, DESIGNERS AND OPERATORS

Means	Use for: Research	Use for: Design	Use for: Operation
Full-scale Fire Test Programs	Advantages: - Direct interpretation - Complete results Disadvantages: - Cost - Limited number of tests Conclusions: - Well suited	Advantages: - Direct interpretation - Possibility of using real road vehicles Disadvantages: - Cost - Limited number of tests - Geometry of the test facility Conclusions: - This solution depends on the importance and specific problems of the project (e.g., Memorial Tunnel)	Advantages: - Direct interpretation Disadvantages: - Cost - Limited number of tests Conclusions: - Unrealistic if not associated with other objectives
Tunnel Fire Tests Before or Under Operation (aimed at optimizing ventilation responses in fire event)	Advantages: - Partial results with full-scale facilities - Numerous different situations Disadvantages: - Lack of information due to the limited number of sensors Conclusions: - Useful but partial results	Advantages: - Accumulation of experience useful to choose a system - Test performed with real ventilation systems Disadvantages: - Limited number of tests Conclusions: - Useful	Advantages: - Shows to the operators how the ventilation reacts - Fire departments are very interested in expected situation Disadvantages: - No operation possible during the tests Conclusions: - Well suited
Tunnel Fire Tests Before or Under Operation (aimed at operators and fire department training)	Advantages: - Visual observations possible Disadvantages: - Lack of information due to the absence of sensors Conclusions: - Not suited	Advantages: - Test performed with real ventilation systems Disadvantages: - Limited analysis due to the lack of measurements Conclusions: - Not well suited	Advantages: - Representative situation Disadvantages: - No operation possible during the tests Conclusions: - Well suited
Reduced Scale Models	Advantages: - Many tests possible - Possible to study global laws governing specific situations Disadvantages: - Needs full-scale reference tests for transposition to real situations Conclusions: - Useful method for research	Advantages: - Cost lower than full-scale tests Disadvantages: - Linked to the limitations induced by the similarity laws Conclusions: - Very difficult to conclude that the results are representative of full-scale situations	Advantages: - Cost Disadvantages: - Linked to the limitations induced by the similarity laws - No respect of time basis Conclusions: - Possibly unrealistic but demonstrative
Numerical Models (CFD)	Advantages: - Possible to study many different situations - Information on flow structures unattainable with other methods Disadvantages: - The conclusions must be correlated to existing experimental references Conclusions: - Useful method for research	Advantages: - Possible to get an optimization by the use of different assumptions Disadvantages: - The model requires qualification Conclusions: - Useful method for projects, if validated	Advantages: - Possible to describe the physical conditions in several locations of the tunnel Disadvantages: - Theoretical results lead to theoretical conclusions Conclusions: - The adaptation depends on the use of the model

Source: PIARC (*21*).

(i.e., radiative smoke properties, generation of soot, and turbulence models).

Several statements can be made based on the studies, tunnel fire events statistics, experience, and tunnel fire tests:

- A tunnel by nature is a highly risky environment. No tunnel is absolutely safe regardless of how it was designed and what types of fire life safety systems were installed. The goal of the design, operation, and maintenance is to make a tunnel as safe as possible based on previous experience, on present knowledge, and on the development of technical equipment. The key element is prevention of tunnel fire.
- Most tunnels experience fires. However, most of the tunnel events are generally small in scale and involve cars and vans.
- Major tunnel fires that involve heavy goods vehicles (HGVs) with dangerous goods and fuel tankers, although rare, can be severe in the tunnel environment. Consequences of tunnel fires can be disastrous for occupants, tunnel structures, and the economy.
- Severe tunnel fires are rare and happen less often than fires on open roads. Cumulatively, the number of people killed in road tunnels worldwide is fewer than 200, including those killed in collisions. Fewer than 20 tunnels worldwide have suffered substantial structural damages as the result of a fire emergency.
- Road tunnel fires cannot be completely eliminated until vehicle fires are eliminated.

Analysis of the catastrophic tunnel fire events resulted in the following conclusions:

- Fires develop much more quickly than expected. Many known actual tunnel fires and fire curves show a very fast development during the first 5 to 10 (sometimes 15) min. The gradient of temperature is steep and the emission of heat and smoke are very important.
- Fire temperatures in excess of 1000°C (1832°F) can be achieved.
- Smoke volumes are higher than expected from an early stage of the fire growth.
- Fire spread between vehicles occurs over a much greater distance than had been expected previously (e.g., more than 200 m or 656 ft in the Mont Blanc Tunnel).
- The road tunnel users behaved unexpectedly, such as:
  - Did not realize the danger to which they were exposed.
  - Failed to use the safety infrastructure provided for self-rescue.
  - Wrongfully believed that they were safer in their cars than if they used the self-rescue safety systems.
  - Chose to stay in their vehicles during the early stages of a fire because they did not want to leave their property.
  - Realized too late the danger they had placed themselves in, by which time it was too late to self-rescue.

Safety is a result of the integration of infrastructural measures, operation of the tunnel, and user behavior, as well as preparedness and incident management. The assessment of fire safety in tunnels is a complex issue, where broad multidisciplinary knowledge and application of different physical models are necessary to explore the causes and development of fires and evaluate measures to prevent and reduce their consequences.

A design fire is an idealization of a real fire that might occur. A design fire scenario is the interaction of the design fire with its environment, which includes the impact of the fire on the geometrical features of the tunnel, the ventilation and other fire safety systems in the tunnel, occupants, and other factors.

Given the range of variables and human behavior nobody can precisely predict every fire scenario. The key design fire scenarios relevant to fire safety in tunnels are:

- For ventilation and other systems (e.g., fixed fire suppressions) design and assessment;
- For egress analysis;
- For thermal action on structures;
- For the safety of tunnel fire equipment; and
- For work on tunnel construction, refurbishment, repair, and maintenance.

A design fire scenario represents a particular combination of events associated with:

- Type, size, and location of ignition source;
- Type of fuel;
- Fuel load density and fuel arrangement;
- Type of fire;
- Fire growth rate;
- Fire's peak HRR;
- Tunnel ventilation system;
- External environmental conditions;
- Fire suppression; and
- Human intervention(s).

Design fires in tunnels are usually given as the peak fire HRR, although it has become more common for engineers to combine the peak HRR with the fire growth rate. Some estimates of the HRR use weighting of the burning components of a vehicle to incorporate burning efficiency, which implies that the fire may not consume the entire heat load available. The leftover content is typically in the form of either a char residue or as soot and smoke particles displaced by the combustion gas stream.

The magnitude and development of fire depends on:

- Vehicle combustion load (often called the fuel load)
- Source of ignition
- Intensity of ignition source
- Distribution of fuel load in the vehicle

- Fire propagation rate
- Tunnel and its environment.

Table 38 summarizes the main design fire variables and provides the ranges for these variables. The table illustrates that time-dependent design fire variables depend on a number of factors to be studied. The table was developed for this effort based on the literature review.

New energy carriers can lead to explosions with catastrophic consequences when there is a fire. Although they do not necessarily mean higher risks, they do represent a new situation and imply new risks. Systems, not only components, need to be tested to study different possible scenarios and to develop models for these scenarios. When the scenarios are described in a representative way, technical safety solutions, mitigation systems, and rescue service tactics can be developed. It is also important to study how the different systems (detection, ventilation, mitigation) interact and how the models developed are altered depending on the scenario. The field of new energy carriers is very diverse and constitutes many different fields of research. More research is needed concerning how safety in tunnels is affected by the introduction and development of new energy carriers.

Fires can develop inside vehicles or outside in a cargo container. As fires develop inside a vehicle heat builds up, leading to elevated gas temperatures within the enclosure. The elevated temperatures will in turn have a significant impact on the growth rate of the fire. Elevated gas temperatures will pre-heat materials that have not been ignited and potentially accelerate flame spread. Gas temperatures in an enclosure can be affected by the size of the enclosure, the ventilation into the enclosure, and the fire HRR.

The development of fires inside vehicles depends on a number of factors including:

- Fire performance of interior materials and features,
- Fire performance of vehicle cargo,
- Size and location of the initiating fire event or ignition scenario,
- Size of the enclosure where the fire is located, and
- Ventilation into the enclosure.

Specification of a design fire may include the following phases:

- The Incipient Phase is characterized by the initiating source, such as smoldering or flaming fire.
- The Growth Phase is the period of propagation spread, potentially leading to flashover or full fuel involvement.
- The Fully Developed Phase is the nominally steady ventilation or fuel-controlled burning.
- The Decay Phase is the period of declining fire severity.
- The Extinction Phase is the point at which no more heat energy is being released.

Simple heat transfer equations do not allow for the making of a direct correlation between the time–temperature curve and the time–heat release curve. It appears that the known fire growth rates follow the super fast (highest increasing rate measured) temperature rise in the time–temperature curves. However, ultrafast HRR curves are often allowed for the design.

Tunnel ventilation systems are still the primary tunnel fire life safety system for controlling smoke and providing a tenable environment for evacuation. There are many types of tunnel ventilation systems.

TABLE 38
MAIN DESIGN FIRE VARIABLES

Time Dependent Design Fire Variables	Values Range	Design fire variables are a function of:
Fire Size—Maximum FHRR	(1.5 MW–300 MW)	Type of vehicle (cars, buses, HGVs, tankers; alternative fuel)
Fire Growth Rate (slow, medium, fast, ultra fast)	0.002–0.178 kW/s^2 as high as 0.331 kW/s^2 measured at one test	Type of cargo including bulk transport of fuel
Fire Decay Rate	0.042–0.06 (min^{-1})	Fire detection system and delay in activation of FLS systems
Perimeter of Fire	Car—truck perimeter	Ventilation profile
Maximum Gas Temperature at Ceiling	110ºC–1350ºC (212ºF–2462ºF) (higher with FCV)	Fire suppression system
Fire Duration	10 min–2 days	Tunnel geometry
Smoke and Toxic Species Production Rate	20–300 m^3/sec	- tunnel width, height, cross section, length
Radiation	From 0.25 to 0.4 of total heat flux up to 5,125 W/m^2 (1,625 Btu/hr/ft^2)	- volume (available oxygen)
Flame Length		- shape of tunnel, grade
		- location of exits
		Tunnel drainage system

- Although longitudinal ventilation controls smoke, it may increase the fire HRR and fire growth rate once air velocities are high. It may also increase the flame length and help the fire to spread farther. However, recent fire tests concluded that the affect of longitudinal ventilation on fire growth and fire HRR was previously significantly overestimated.
- 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 bi-directional traffic tunnels or when vehicles are trapped on both sides of the fire. This system relies on smoke stratification and smoke capture, produces low longitudinal air velocities, and does not impact the fire growth and HRR as much. However, this system is 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 duct, may be needed to avoid structural collapse.

Ventilation has an influence on the fire development that does not always conform to expectations:

- Owing to increased ventilation the fire development for a car can be slowed if the fire is ignited at the front of the car. This is in contrast to the accepted view of supposed accelerated development resulting from ventilation.
- The influence of increased ventilation on the observed fire behavior depends on the ignition location. Note that 95% of fires begin in the engine compartment (i.e., at the front).
- Under the influence of a high-ventilation velocity, the fire development accelerates for a covered load at a rate 2 to 3 times faster. The fire size was 20% to 50% higher owing to a high-ventilation speed.
- There could be a negative effect of ventilation because forced ventilation may cause significant 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.

Tenable environment is well-defined by NFPA 502 and other standards. To develop a time-of-tenability curve, the project must develop:

- A fire heat release curve as a function of time,
- A design evacuation (egress) curve as a function of time, and
- A design systems response curve as a function of time.

A tenability map indicates all time steps and the resulting impact on casualties and tunnel structure. It allows for predicting how long the environment will be tenable in the tunnel and helps to decide what needs to be done to achieve fire life safety goals.

A fire suppression industry offers to control the fire size, reducing the maximum HRR and fire growth by applying a fixed fire suppression system. Once a fire is detected early by a reliable fire-detection system, the fire protection system could be activated within several minutes, taking the fire under control and not allowing it to grow further or spread to other vehicles. It may also suppress a small fire.

- It is essential that the detection system be capable of detecting a small fire (in the order of 1–5 MW). If this 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. The fire may continue growing, resulting in the production of dangerous steam and may cause concrete spalling. Sprinklers must not be turned off before the fire is completely extinguished or being suppressed by the fire department. Early sprinkler deactivation may lead to explosions and structural collapse.
- Water droplets will be affected by ventilation. Longitudinal airflow must be selected to ensure an appropriate droplet spread and mass flow. Ventilation system performance is also affected by sprinkler operation. The main idea is to acquire a well-designed system with a reliable quick fire-detection system to start these systems before the fire gets too large.
- Additional considerations need to be given to the impact of a fixed fire suppression system on smoke stratification, visibility, and steam generation during the evacuation phase.
- If the sprinkler system is activated early enough, can ventilation be reduced or eliminated and what will be the impact on smoke production? Additional studies may be required.
- There is still a lack of experience in the United States with tunnel fire suppression systems. This system has pros and cons and its benefits need to be evaluated for each tunnel because every tunnel is unique.
- A structural protection industry offers coatings and protection materials to protect the tunnel structure from damage. However, what will this do to the safety of the tunnel environment by not allowing heat to dissipate through the tunnel walls? What will happen to the tunnel temperatures and the ability of first responders to enter the tunnel?

Major progress has recently been made in fire-detection technology. Listed and approved video flame and smoke detectors that have been tested in the tunnel environment are now available. Tunnel safety starts with fire detection, which will cause all systems to activate and notify people to evacuate. Every second is accounted for in the major tunnel fire event, especially during evacuation and the initial phase of fire development. Several countries provide standard requirements for detection time and maximum fire size for detection.

The survey conducted for this effort proved that fires in road tunnels are rare events. Here are some findings and lessons learned from the survey:

- More fires occur in the busiest tunnels. In most of the U.S. tunnels, fires happen 1 or 2 times a year; however, most of them are small and do not result in any significant losses. The most significant fires occur with trucks (HGVs). In these cases, casualties are likely.
- Many agencies would consider protection tunnels with the fixed fire suppression system, if proven effective. Future studies are required to address this area of tunnel technology.
- Most of the agencies rely on closed circuit television (CCTV) for fire detection and incident detection. This technology needs to be further developed for heat and smoke detection, as well as be tested and listed for fire-detection applications in tunnels.
- There is a need to continue developing tunnel ventilation systems and ventilation response in conjunction with other systems such as fixed fire suppression systems.
- Specifications for the devices need to be developed further. Reliable and maintainable devices could become commercially available that are designed for a particular tunnel environment, considering the typical tunnel cleaning and washing operation, chemicals and pollutants present, and dirt and debris build up. One example is locating a commercially available pull station system for a roadway tunnel that has long-time reliability.

One item for future study that was expressed by many of the national and international tunnel agencies is the need to develop a tunnel fire system computer simulator for operators to manage fires. Similar research programs have been successfully accomplished in Sweden and Austria. Learning from their experience might help tunnel operators, first responders, and tunnel agencies to better understand their tunnels and train their personal accordingly.

Many research works and studies have been done in the United States and worldwide on the development of design for tunnel fires. However, there are still knowledge gaps in many areas including:

1. Training and education
    - Training of tunnel operators and first responders by developing, for example, a virtual fire/systems simulator.
    - Better understanding of the human behavior of tunnel users and operators, as well as providing a means of public education. During emergency situations, human behavior is even harder to predict, as the stress of the situation replaces intellect with curiosity, fear, or even panic. Unfortunately, in general, people are inclined to do the wrong thing in the event of a tunnel fire, such as staying inside their cars instead of heading for the emergency exits. Tunnel emergency management scenarios and procedures must take human behavior into account to be fully effective in saving lives.
2. Operation and commissioning
    - International practice of commissioning tunnel fire life safety equipment and fire fighting procedures using hot smoke tests and burning actual vehicles in the tunnels needs to be evaluated for future national standards' considerations. The best international practice of commissioning tunnel life safety systems using hot smoke tests is not (or seldom) used in national practice. With the exception of several jurisdictions, cold smoke is commonly used to evaluate ventilation system performance simulating tunnel fires. Unfortunately, cold smoke tests cannot replace hot smoke tests. The national standards do not require that systems commissioning hot smoke tests use hot smoke tests.
    - It is advisable to study the experience of the road tunnel operations managing fuel tankers and other dangerous goods. Such experience exists and best practice could be studied for both design and operation. Categorically banning dangerous goods from tunnels may create an adverse economic impact.
3. Physics, numerical modeling, and testing:
    - Correlation between a time–temperature curve and a HRR curve.
    - The impact of passive fire protection materials on the fire HRR and resultant temperatures in the tunnel environment.
    - Verifications through the performance of additional vehicle tunnel fire tests with the special aim of measuring the production rates for smoke and toxic gases (e.g., CO, CO_2, and HCN) and factors related to the light absorption by smoke (e.g., mass optical densities). Full-scale fire tests may need multi-agency support and possibly international collaboration.
    - Evaluation of the state of the art of numerical fire and evacuation simulations. Capabilities of capturing the effects of mitigating measures, such as early or delayed suppression (e.g., water-based, foam, fixed, and mobile), ventilation, insulation, smoke compartmentation, operator interventions, and so forth, need to be included.
    - Post-cooling spalling mechanism and structural protection of tunnel walls by means of a fixed fire suppression system. This also requires a review of the experiences with the use of fixed fire suppression systems in managing tunnel fires and additional testing of the systems.
    - Harmonization of the design parameters for numerical fire and evacuation simulations.
    - Numerical modeling of sprinkler system impact on flame and fire size needs CFD code development and validation.
    - Development of uniform methods of assessment and the validation of numerical modeling results.

- Coupling of numerical aerodynamic and fire simulation with structural calculation methods and eventually with evacuation models.
- Additional studies and analytical modeling is needed on alternative fuel vehicle fires in the tunnel environment.

4. Development of specifications, regulations, and technology:
   - Further development of CCTV-based fire-detection technology tested and listed for tunnel applications.
   - Further development of tunnel ventilation systems, and the ventilation response in conjunction with other systems, such as fixed fire suppression systems.
   - Regulations and guidance need to provide better consideration of the activity of all systems that interact in a tunnel. Integrated approaches shall be applied to tunnel fire safety.
   - Consideration shall be given for technical innovations that allow for more ambitious safety objectives.
   - Specifications for the tunnel fire life safety devices. Reliable and maintainable devices could become commercially available that are designed for the tunnel environment, considering the typical tunnel cleaning and washing operations, chemicals and pollutants present, and dirt and debris build up.
5. Risk of tunnel fires:
   - It is important that the frequency of tunnel fires be evaluated against their consequences for developing a weighted risk impact.
   - Risk of fires in combined use tunnels need to be evaluated and special recommendations be provided on design approach of combined use tunnel fire safety design.
   - The field of new energy carriers is very diverse and new types of energy carriers are being introduced. The safety of tunnels that allow alternative fuel vehicles might not rely on component tests of such vehicles, but on the testing of entire systems using realistic scenarios. Such aspects as possible gas detonations with low ventilation require systematic research. Risk to the tunnel structure as the result of alternative energy carriers' fires requires additional research work.

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GLOSSARY

Accident—An incident followed by the development of unsafe situations for people in a tunnel.

Alternative fuel—A motor vehicle fuel other than gasoline and diesel.

Backlayering—The reversal of movement of smoke and hot gases counter to the direction of the ventilation airflow.

Combustible—Capable of undergoing combustion.

CCTV—Closed circuit television.

Combustible liquid—Any liquid that has a closed-cup flash point at or above 100°F (37.8°C), as determined by the test procedures and apparatus set forth in Section 4.4 of NFPA 30, Flammable and Combustible Liquids Code. Combustible liquids are classified according to Section 4.3 of NFPA 30.

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

Deluge system—An open fixed fire fighting system activated on a zone-by-zone basis. Operation can be automatic or manual.

Fire emergency—The existence of, or threat of, fire or the development of smoke or fumes, or any combination thereof, that demands immediate action to correct or alleviate the condition or situation.

Fire growth rate—Rate of change of the fire's heat release.

Fire suppression—The application of an extinguishing agent to a fire at a level such that open flaming is arrested; however, a deep-seated fire will require additional steps to assure total extinguishment.

Fixed water-based firefighting system (or fixed fire suppression system; FFSS)—A system permanently attached to the tunnel that is able to spread a water-based extinguishing agent in all or part of the tunnel.

Flammable liquid—Any liquid that has a closed-cup flash point below 100°F (37.8°C), as determined by the test procedures and apparatus set forth in Section 4.4 of NFPA 30, Flammable and Combustible Liquids Code, and a Reid vapor pressure that does not exceed an absolute pressure of 40 psi (76 kPa) at 100°F (37.8°C), as determined by ASTM D 323, Standard Test Method for Vapor Pressure of Petroleum Products (Reid Method). Flammable liquids are classified according to Section 4.3 of NFPA 30.

Flashover—A sudden transition from localized to generalized burning where all of the items inside a vehicle or compartment ignite.

Heat release rate (HRR)—The rate at which heat energy is generated by burning expressed as Btu/s or megawatts (MW).

Length of tunnel—The length from face of portal to face of portal that is measured using the centerline alignment along the tunnel roadway.

Point of safety—An exit enclosure that leads to a public way or safe location outside the structure, or an at-grade point beyond any enclosing structure, or another area that affords adequate protection for motorists.

Road tunnel—An enclosed roadway for motor vehicle traffic with vehicle access that is limited to portals.

Scenario analysis—The analysis of the consequences of a wide range of accidents in a tunnel.

Self-rescue—People leaving the hazardous area or dangerous situation without the help of trained or professional rescuers (tunnel personnel or fire fighters).

Standpipe system—An arrangement of piping, valves, hose connections, and allied equipment installed in a building or structure, with the hose connections located in such a manner that water can be discharged in streams or spray patterns through attached hoses and nozzles, for the purpose of extinguishing a fire, thereby protecting a building or structure and its contents in addition to protecting the occupants.

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

Water mist systems—Fixed fire fighting systems that operate by discharging very small droplets of water.

APPENDIX A

Survey Questionnaire

The following is a questionnaire administered to staff at state DOTs and targeted individuals.

NCHRP Project 20-05
Topic 41-05
Design Information on Fires in Road Tunnels

PURPOSE

This survey is intended to identify the current state of practice regarding the Design Information on Fires in Road Tunnels. This survey is part of an NCHRP Synthesis project, which is funded by various state transportation agencies. In addition to the survey, the final report will include a literature review and case studies based on information from the survey respondents. Results of this effort will provide more readily available information to individuals and agencies interested in Tunnel Safety and Fires in Road Tunnels.

RESPONDING AGENCY/ORGANIZATION INFORMATION

The following data will help us identify the specific agency or organization you are affiliated with and to allow us to contact you in the future regarding the outcome of this project.

1. First Name
2. Last Name
3. Title
4. Company Name
5. Street Address
6. Apt/Suite/Office
7. City
8. State
9. Postal Code
10. Country
11. E-mail Address
12. Phone Number
13. Fax Number
14. Mobile Phone
15. URL

YOU MAY SAVE THIS SURVEY TO FINISH AND SUBMIT AT ANOTHER TIME.
HOWEVER, PLEASE COMPLETE IT NO LATER THAN FEBRUARY 25, 2010.

If you have any questions regarding this survey, please contact Dr. Igor Maevski, PhD, PE of Jacobs Engineering at (212) 481-9460 (igor.maevski@jacobs.com).

INSTRUCTIONS

Please answer all of the following questions to the best of your abilities and feel free to submit relevant materials that you believe would provide additional information and/or clarification. If you cannot submit the attachments through this on-line survey, you may send it to my e-mail address. If your agency manages several tunnels, please fill out a separate questionnaire form for each tunnel.

If you believe another individual or department within your agency or organization is more suited to complete the survey or a portion of it, please forward the link to that individual or department. However, please make sure to note who is the recipient.

SECTION 1—BACKGROUND QUESTIONS:

General Information

16. What is the tunnel agency name?

17. What is the name of the tunnel?

18. What year was the tunnel built or expected date of completion?

19. Is the tunnel under supervision?
    - ☐ 24-hour supervision (skip 4a)
    - ☐ Not supervised
    - ☐ Supervised, except night time

20. What is the normal traffic operation?
    - ☐ Uni-directional
    - ☐ Bi-directional

21. When does the tunnel operate in bi-directional mode? (Please check all that apply.)
    - ☐ Normally
    - ☐ At night time
    - ☐ Off-peak hours
    - ☐ Occasionally
    - ☐ During construction/maintenance in other tube
    - ☐ Other
    - ☐ Never

22. What type of vehicles use the tunnel? (Please check all that apply.)
    - ☐ Cars only
    - ☐ Buses only
    - ☐ Cars/buses only
    - ☐ Cars/buses/trucks, but not HGV
    - ☐ Special trucks (military)
    - ☐ All vehicles, including HGVs
    - ☐ Gasoline tankers—freely
    - ☐ Gasoline tankers—supervised when tunnel is closed for normal traffic

Fire Incidents Information

23. How many annual vehicle fire incidents happen in this tunnel (average)?
    - ☐ Never happened before
    - ☐ Happened once in a lifetime
    - ☐ Less than 1 every year
    - ☐ From 1 to 2 every year
    - ☐ From 2 to 5 every year
    - ☐ Happens every month

24. What were the most severe vehicle fire incidents in this tunnel? (Please check all that apply.)
    - ☐ Motorcycle fire
    - ☐ Passenger car fire
    - ☐ Multiple passenger cars (2–4 vehicles)
    - ☐ Vans
    - ☐ Bus
    - ☐ Heavy goods truck fire
    - ☐ Multiple truck fire
    - ☐ Tanker fire
    - ☐ Alternative fuel vehicle
    - ☐ Other:

25. Was there any damage made to this tunnel as a result of the fire incident?
    - ☐ No damages. No impact on tunnel operation
    - ☐ No damages. Tunnel was closed for operation for 30 min or more
    - ☐ Minor damages (no structural damage)
    - ☐ Structural damage that required tunnel closure for an extended period of time

26. Were there any casualties from the fire?
    ☐ Never ☐ Minor ☐ Major

27. Has the fire department ever been involved in fire fighting in this tunnel?
    ☐ Never
    ☐ Occasionally
    ☐ Every time

28. Was there an investigation performed after the fire?
    ☐ Every time ☐ Occasionally, depending on fire size
    ☐ Never ☐ Once

29. What was the estimated maximum fire size?

30. What was the longest duration of the fire?

31. Have you videotaped any car fire incidence?

32. Can you share the video information?

33. Has your agency been successful in managing the fire event? (Please provide an explanation.)
    ☐ No (please explain):
    ☐ Yes (please explain):
    ☐ Partially (please explain):

34. Do you have an emergency response plan in place?

35. Please explain what are the strengths of your agency's fire management program?

36. What barriers or difficulties have you or your organization encountered in implementing fire management? (Please check all that apply.)
    ☐ Technical (please explain):
    ☐ Political (please explain):
    ☐ Legal (please explain):
    ☐ Organizational/institutional (please explain):
    ☐ Staffing/resources (please explain):
    ☐ Other (please explain):
    ☐ None

37. What are your suggestions on how these barriers can be overcome?

Fire Detection, Fire Protection, Communication

38. What kind of fire detection system does the tunnel have? (Please check all that apply.)
    ☐ Heat detection (linear) ☐ Heat detection (other than linear)
    ☐ Smoke detection ☐ Pull station
    ☐ CCTV ☐ Video surveillance technology
    ☐ Phones ☐ Other:

39. What kind of fire protection system does the tunnel have? (Please check all that apply.)
    ☐ Fire hydrants along the tunnel; ☐ Standpipe system with fire hose connections (dry or wet)
    ☐ Fire extinguishers in the tunnel ☐ Fire sprinkler system
    ☐ Foam system ☐ Fire apparatus in the tunnel

40. What kind of fire life safety system does this tunnel have? (Please check all that apply.)
    ☐ Tunnel ventilation ☐ Emergency egress
    ☐ Egress pressurization ☐ Other:

41. What communication systems are used by rescue personnel and others for fire emergency?

42. Please explain how quickly your agency is able to detect and clear routine traffic crashes inside this tunnel?

43. Do you have tow trucks in your agency or do you contract out for theses services?
☐ Have tow trucks ☐ Contract out for tow trucks ☐ Other (Please explain):

44. Are you concerned that your tunnel may not have an adequate fire/life safety system to manage a significant fire event? (Please explain.)

Design

45. Does your agency have their own standard for tunnel design and for fire rating?
☐ Yes ☐ No ☐ Other (Please explain):

46. What guidance and standards are provided to designers to address the fire design issues for new and for retrofitted tunnels? (Please check all that apply.)
☐ NFPA 502 ☐ ASHRAE ☐ FHWA ☐ Other:

47. Do you specify the design fire size and fire curve to the designers? (Please check all that apply.)
☐ Fire size
☐ Fire curve
☐ Required to follow the NFPA 502
☐ Leave it up to the consultant
☐ Leave it up to the Authority Having Jurisdiction (AHJ)
☐ Other (Please explain):

48. Is security blast design included in the requirements? (Please check all that apply.)
☐ Security ☐ Blast design ☐ None

49. Who is the Authority Having Jurisdiction (AHJ)?
☐ Our agency ☐ Fire department ☐ Don't know ☐ Other:

50. Do you apply a risk assessment approach for fire engineering?
☐ Yes ☐ No ☐ Other (Please explain):

51. How do you handle specific risk that cannot be mitigated?

52. What traffic management and safety innovations are deployed or planned to minimize or eliminate problems such as congestion and traffic management during a fire?

53. Do you have an emergency response plan in place?
☐ Yes ☐ No ☐ Other (Please explain):

54. Which agency has the role of incident commander?

55. What best practices can you share in the areas of prevention, mitigation, and recovery from fire incidence?

56. Would you consider protection of the tunnel with the fixed fire suppression system (sprinkler system) to meet the new NFPA 502 Max Fire Heat Release Rate Requirements, if proven effective?
☐ Yes ☐ No ☐ Other (Please explain):

57. Have you identified gaps in research and design for tunnel fire safety, or fire detection and protection?
☐ No ☐ Yes (Please explain):

58. Can you suggest strategies to eliminate the gaps and improve tunnel fire safety?

59. Would you consider a fire event to be similar to a seismic event for design purposes? (Example design for the fire event which has a high probability to happen once in 500 years or 2,500 years?)
☐ Yes ☐ No ☐ Other (Please explain):

60. What is this tunnel life's expectancy?

61. Do you have any additional suggestions and thoughts on the design for fire emergency?

62. Please identify any research that you would like to see performed to help in the implementation of fire safety systems.

Operation, Maintenance, Repair, Rehabilitation

63. What types of exercises and other training are provided to staff and first responders to ensure proficiency in response to an incident and how is the training evaluated?

64. Would you need additional training tools for operators to manage a fire?
☐ Tunnel fire/systems simulator ☐ No ☐ Other (please explain):

65. What equipment and materials are pre-positioned for response and recovery to a fire, such as for the quick removal of disabled vehicles?

66. What is considered an acceptable response time?

67. How often are tunnels and emergency response equipment inspected and tested?

68. What methods are used to inspect the structural integrity of the tunnel structure both routinely and after a fire? What materials are used to repair concrete after a fire?

69. If you were to start a new tunnel project, what key elements would you incorporate in the design and construction to aid you in tunnel fire incident management?

70. Are the lighting and emergency communication systems designed to survive major fire events?
☐ Yes
☐ No (please explain how to ensure safe evacuation during an incident that involves major fires):
☐ Other (Please explain):

71. What are the operational protocols for the use of the ventilation system during a fire event?

72. How are the maintenance considerations worked into the design elements of tunnel fire detection and fire suppression systems?

73. Do you actively screen or otherwise monitor truck cargoes entering the tunnel without disrupting the traffic flow?
☐ Yes
☐ No
☐ Other (Please explain):

74. What dangerous cargo is acceptable and how is this enforced?

75. What systems do you have plans for repair or replacement of fire or life safety equipment? (Please check all that apply.)
☐ Tunnel ventilation ☐ Fire suppression ☐ Standpipes
☐ Fire detection ☐ Communication ☐ Emergency lighting
☐ Other (Please explain):

Follow-up

76. Please provide any additional information or suggestions you may have.

77. Please identify any agencies that you would recommend we invite to participate in this survey.

78. If needed, who in your organization could we contact for additional follow-up information?
    - ☐ You may contact me.
    - ☐ Please contact someone else (please provide their name, telephone number, and e-mail address):

THANK YOU FOR YOUR TIME AND PARTICIPATION
IN THIS SYNTHESIS STUDY

If you wish to complete this survey off this online survey, please mail or e-mail by **February 16, 2010** to:

Igor Maevski, PhD, PE,
Jacobs Engineering
Igor.maevski@jacobs.com

APPENDIX B

List of Responding Agencies

Tunnel Agency Name	Name of Tunnel(s)	Street Address (if given) City, State (if given)	Country
Virginia Department of Transportation (VDOT)	1) Downtown Tunnel (First)—EBL 2) Downtown Tunnel (First)—WBL 3) Hampton Roads Bridge Tunnel—EBL 4) Hampton Roads Bridge Tunnel—WBL 5) Midtown tunnel 6) Monitor–Merrimac Memorial Bridge Tunnel 7) NAS Runway #29 Underpass	1401 W. Broad Street Richmond, VA	United States
California Department of Transportation	1) Webster Tube 2) Posey Tube 3) Sunrise On Ramp 4) Caldecott Tunnel Complex #1 5) Caldecott Tunnel Complex #2 6) Caldecott Tunnel Complex #3	California	United States
Washington State DOT	1) I-90 Mt. Baker Ridge Tunnel 2) I-90 Mercer Island Tunnel	1411 Yakima Ave. S. Seattle, WA	United States
Korea Expressway Corporation	1) Jookryung 2) Average data for 280 (555 tubes) tunnels	293-1 Sujung-Gu Geumto-dong Seong Nam	South Korea
Pennsylvania DOT	1) Liberty Tunnel 2) Stowe Tunnel	45 Thoms Run Rd. Bridgeville, PA	United States
Colorado DOT—Region 1, Maintenance Section 9	Eisenhower/Johnson Memorial Tunnel (2 bores, 1 tunnel unit)	P.O. Box 397 Idaho Springs, CO	United States
Chesapeake Bay Bridge and Tunnel	1) Thimble Shoals 2) Chesapeake Channel	Cape Charles, VA	United States
Mak Hungary	M6 South	Pázsit Street 13 Budapest	Hungary
Maryland Transportation Authority	1) Fort McHenry Tunnel 2) Baltimore Harbor Tunnel	300 Authority Drive Baltimore, MD	United States
Ministère des transports du Québec	Ville-Marie & Lafontaine	640 Viger Ouest Montreal	Canada
Oregon DOT	1) Oneonta 2) Cape Creek 3) Elk Creek 4) Toothrock 5) Arch Cape 6) Salt Creek 7) Sunset 8) Knowles Creek 9) Vista Ridge Twin Tunnels	355 Capitol St. NE, Room 301 Salem, OR	United States
Swedish Road Administration	Gotatunnel	Gothenburg	Sweden
Sydney Harbour Tunnel Company	Sydney Harbour Tunnel	130 Mount Street North Sydney	Australia
The Port Authority of New York & New Jersey	The Holland Tunnel	13th & Provost Streets Jersey City, NJ	United States
Vägverket	Södra Länken	Sundbybergsvägen 1 Solna	Sweden

APPENDIX C

Summary of Survey Questionnaire Responses

Appendix C has two parts, which are taken from the survey results. The first part contains the national data and the second part is the international data. Some of the tunnels may make multiple choices for the "please check all that apply" questions. The survey data below are shown based on the **number of tunnels,** instead of number of agencies (which may cover multiple tunnels).

PART 1: NATIONAL DATA

Section 1 Background Information

The first 15 questions were used so that the researchers could contact the respondent for additional information, if necessary. All this information is shown below.

Section 2 General Information

Questions 16 and 17 were used to obtain the agency name and the name of the tunnels, respectively. All this information is shown below.

18. What year was the tunnel built or expected date of completion?
See below chart

19. Is the tunnel under supervision?
Yes, 24 hr—19
Yes, except at night—0
No—11

20. What is the normal traffic operation?
Uni-directional—26
Bi-directional—4

21. When does the tunnel operate in bi-directional mode? (Please check all that apply.)
Normally—4
At night time—2
Off-peak hours—2
Occasionally—0
During construction/maintenance in other tube—9
Never—16
Other (Please explain)—1 (emergency evacuation)

Tunnel agency name	Number of surveys submitted	Number of tunnels	Year tunnel was built
Virginia Department of Transportation (VDOT)	7	1) Downtown Tunnel (First)—EBL 2) Downtown Tunnel (First)—WBL 3) Hampton Roads Bridge Tunnel—EBL 4) Hampton Roads Bridge Tunnel—WBL 5) Midtown tunnel 6) Monitor–Merrimac Memorial Bridge Tunnel 7) NAS Runway #29 Underpass	1) 1986 2) 1952 3) 1974 4) 1958 5) 1962 6) 1992 7) 1977
California Department of Transportation	6	1) Webster Tube 2) Posey Tube 3) Sunrise On Ramp 4) Caldecott Tunnel Complex #1 5) Caldecott Tunnel Complex #2 6) Caldecott Tunnel Complex #3	1) 1963 2) 1927 3) 2006 4) 1937 5) 1937 6) 1963
PennDOT	2	1) Liberty Tunnel 2) Stowe Tunnel	1) 1924 2) 1909
CDOT—Region 1, Maintenance Section 9	1	Eisenhower/Johnson Memorial Tunnel (2 bores, 1 tunnel unit)	1973/1979
Chesapeake Bay Bridge and Tunnel	2	1) Thimble Shoals 2) Chesapeake Channel	1) 1964 2) 1964
Maryland Transportation Authority	1	1) The Fort McHenry Tunnel 2) The Baltimore Harbor Tunnel	1) 1985 2) 1957

(*continued on next page*)

Oregon DOT	1	1) Oneonta 2) Cape Creek 3) Elk Creek 4) Toothrock 5) Arch Cape 6) Salt Creek 7) Sunset 8) Knowles Creek 9) Vista Ridge Twin Tunnels	1) 1914 2) 1921 3) 1932 4) 1932 5) 1937 6) 1938 7) 1940 8) 1958 9) 1969
The Port Authority of New York & New Jersey	1	The Holland Tunnel	1927
WS DOT	1	1) I-90 Mt. Baker Ridge Tunnel 2) I-90 Mercer Island Tunnel	1) 1990 2) 1990

22. What type of vehicles use the tunnel? (Please check all that apply.)
Cars—24
Buses—24
Trucks—24
HGV—19
Special trucks (military)—12
Gasoline tankers: freely—6
Gasoline tankers: supervised when tunnel is closed for normal traffic—4
Other vehicles—10

Section 3 Fire Incidents Information

23. How many annual vehicle fire incidents happen in this tunnel (average)?
No occurrence (skip questions 9–18)—11
Happened once in lifetime—0
Less than one every year—2
From 1 to 2 every year—14
From 2 to 5 every year—1
Happens at least once a month—0

24. What were the most severe vehicle fire incidents in this tunnel? (Please check all that apply.)
Motorcycle fire—0
Passenger car fire—13
Multiple passenger cars (2–4 vehicles)—7
Vans—6
Bus—1
Heavy goods truck fire—10
Multiple trucks fire—0
Tanker fire—0
Alternative fuel vehicle—0
Other—1 (Recreational vehicle, motor home)

25. Was there any damage made to this tunnel as a result of the fire incident?
No damages. No impact on tunnel operation—2
No damages. Tunnel was closed for operation for 30 min or more—0
Minor damages (no structural damage)—15
Structural damage which required tunnel closure for an extended period of time—1

26. Were there any casualties from the fire?
None—16
Minor—2
Major—0

27. Has the fire department ever been involved in fire fighting in this tunnel?
Never—1
Occasionally—1
Every time—14

28. Was there an investigation performed after the fire?
Every time—6
Occasionally, depending on fire size—6
Never—1
Once (Please explain when)—5

29. What was the estimated maximum fire size?
MD (2 tunnels)—Single tractor trailer truck
CO—15 to 20 MW
CA (5 tunnels)—small car fire

30. What was the longest duration of the fire?
MD (2 tunnels)—about 20 min
CO—25 min
WA (2 tunnels)—15 min

31. Have you videotaped any car fire incidence?
VA DOT (6 tunnels)—Yes
VA DOT (1 tunnel)—No
PA DOT—No
MD (2 tunnels)—No
NY/NJ Port Authority—Yes
CO—No
WA DOT (2 tunnels)—Yes

32. Can you share the video information?

33. Has your agency been successful in managing the fire event? (Please provide an explanation.)
No—0
Yes—13
Partially—6

34. Do you have an emergency response plan in place?
Yes—22

35. Please explain what are the strengths of your agency's fire management program?
PA DOT—local response time under 10 min
PA DOT—EMS/FIRE response under 10 min
MD (2 tunnels)—Exhaust fan fire pattern moved smoke away from motorists caught behind the fire and the fire department responded quickly to extinguish the fire. The quick response was the result of quarterly meetings between the fire department and the Authority to discuss response plans.
NY/NJ Port Authority—Coordination of multiple entities
VA CBBT (2 tunnels)—3,000 gallon tanker truck, wrecker fire trucks, wall fire extinguishers, fire pumps, fire department within 7 miles
WA DOT—Routine testing

36. What barriers or difficulties have you or your organization encountered in implementing fire management? (Please check all that apply.)
Technical (please explain)—2
Political (please explain)—1
Legal (please explain)—0
Organizational/institutional (please explain)—9
Staffing/resources (please explain)—9
Other (please explain)—0
None—15

37. What are your suggestions on how these barriers can be overcome?
NY/NJ Port Authority—Continuous training and revision of policy
WA DOT—More specific training for operations and maintenance staff.

Section 4 Fire Detection, Fire Protection, Communication

38. What kind of fire detection system does the tunnel have? (Please check all that apply.)
Heat Detection (linear)—4
Heat Detection (other than linear)—0
Smoke Detection—0
Pull Station—14
CCTV—18
Video surveillance technology—4
Phones—16
Other (Please explain)—0

39. What kind of fire protection system does the tunnel have? (Please check all that apply.)
Fire hydrants along the tunnel—11
Standpipe system with fire hose connections (dry or wet)—17
Fire extinguishers in the tunnel—20
Fire sprinkler system—2
Foam system—4
Fire apparatus in the tunnel—1

40. What kind of fire life safety system does this tunnel have? (Please check all that apply.)
Tunnel ventilation—20
Emergency egress—9
Egress pressurization—2
Other (Please explain)—0

41. What communication systems are used by rescue personnel and others for fire emergency?
VA DOT (6 tunnels)—STARS
PA DOT—800mhz radio
MD (2 tunnels)—Portable radio and cellular phone
OR DOT (9 tunnels)—Radio, cell phone
NY/NJ Port Authority—Radio
VA CBBT (2 tunnels)—District radio, cell phone statewide radio system
CA DOT (5 tunnels)—call boxes and responding agency comms
CA DOT (1 tunnel)—responding agency comms
WA DOT—Portable radio

42. Please explain how quickly your agency is able to detect and clear routine traffic crashes inside this tunnel?
VA DOT (7 tunnels)—1/2 h to 1 h for routine vehicular incidents; 4 h for incidents involving fatalities
PA DOT—less than 15 min tow trucks on site
MD (2 tunnels)—Detection less than 1 minute
Clearing approx. 20 minutes; or more depending on nature of crash and involvement of injuries
OR DOT (9 tunnels)—Could take 1 h up to 8 h
NY/NJ Port Authority—Detection is continuous and almost instantaneous
VA CBBT (2 tunnels)—Normally less than 20 min

43. Do you have tow trucks in your agency or do you contract out for theses services?
Have tow trucks—14
Contract out for tow trucks—10
Other (Please explain)—6

44. Are you concerned that your tunnel may not have an adequate fire/life safety system to manage a significant fire event? Please explain.
No—12
Yes—19

Section 5 Design

45. Does your agency have their own standard for tunnel design and for fire rating?
Yes—3
No—28
Other (Please explain)—0

46. What guidance and standards are provided to designers to address the fire design issues for new and for retrofitted tunnels? (Please check all that apply.)
NFPA 502—23
ASHRAE—0
FHWA—22
Other (Please explain)—6

47. Do you specify the design fire size and fire curve to the designers? (Please check all that apply.)
Fire Size—9
Fire Curve—0
Require to follow the NFPA 502—17
Leave it up to the Consultant—11
Leave it up to the Authority Having Jurisdiction (AHJ)—7
Other (Please explain)—1

48. Is security blast design included in the requirements? (Please check all that apply.)
Security—9
Blast design—0
Security and blast design—1

49. Who is the Authority Having Jurisdiction (AHJ)?
Our Agency—25
Fire Department—6
Don't know—0
Other (Please explain)—0

50. Do you apply a risk assessment approach for fire engineering?
Yes—10
No—20
Other (Please explain)—0

51. How do you handle specific risk that cannot be mitigated?
MD (2 tunnels)—Response and recovery plans
NY/NJ Port Authority—Conduct series of "table top" drills with agency staff, OEM, and local authorities
CA DOT (6 tunnels)—Engineering judgment with AHJ approval

52. What traffic management and safety innovations are deployed or planned to minimize or eliminate problems such as congestion and traffic management during a fire?
PA DOT (2 tunnels)—Detours are in place
MD (2 tunnels)—Traffic is held prior to entering the impacted tunnels as soon as a fire is reported. Detour routes are pre-planned and signed. All entry points to the tunnel throughway have dynamic message signs and traffic is warned prior to entering when major incidents impact the tunnel.
OR DOT (9 tunnels)—None
NY/NJ Port Authority—Coordinate with agency staff, other agency facilities, police at all levels, other agencies, OEM, and local authorities.
VA CBBT (2 tunnels)—All traffic is held at the toll plazas and emergency crewmen stop traffic at the mouth of the tunnel.
CA DOT (6 tunnel)—Standard traffic operations, including traffic control and law enforcement

53. Do you have an emergency response plan in place?
Yes—31
No—0
Other (Please explain)—0

54. Which agency has the role of incident commander?
VA DOT (7 tunnels)—State police or local responders
PA DOT (2 tunnels)—local EMS/state police
MD (2 tunnels)—We are the incident commanders.
OR DOT (9 tunnels)—Oregon DOT
NY/NJ Port Authority—Depends on emergency and location
VA CBBT (2 tunnels)—Operations
CA DOT (6 tunnels)—State and fire responders
WA DOT—Local fire department

55. What best practices can you share in the areas of prevention, mitigation, and recovery from fire incidence?
VA DOT (7 tunnels)—Perform "after-incident" reviews
MD (2 tunnels)—Mitigation/recovery—Work closely with local fire departments; our staff that does towing, and contract towers to quickly extinguish the fire and get the burned vehicle, and maintenance staff to clean up debris.
OR DOT (9 tunnels)—None
NY/NJ Port Authority—All if permission and non-disclosure agreements are granted

56. Would you consider protection of the tunnel with the fixed fire suppression system (sprinkler system) to meet the new NFPA 502 Max Fire Heat Release Rate Requirements, if proven effective?
Yes—16
No—6
Other (Please explain)—9

57. Have you identified gaps in research and design for tunnel fire safety, or fire detection and protection?
No—29
Yes (Please explain)—2

58. Can you suggest strategies to eliminate the gaps and improve tunnel fire safety?
MD (2 tunnels)—Consider co-development of specifications (industry standards) for the devices along with the fire-code requirements such that

reliable and maintainable devices are commercially available that are designed for the tunnel environment. Consider the typical tunnel cleaning/washing operation, chemicals and pollutants present, and dirt/debris build up (e.g., locating a commercially available pull station system for the roadway tunnel application that is reliable over a long time period has proven difficult).

59. Would you consider a fire event to be similar to a seismic event for design purposes? (Example design for the fire event which has a high probability to happen once in 500 years or 2,500 years?)
Yes—22
No—12
Other (Please explain)—1

60. What is this tunnel life's expectancy?
VA DOT (7 tunnels)—Design life is 50 years; however, life expectancy typically exceeds 100 years.
PA DOT (2 tunnels)—150 years
MD (2 tunnels)—100 years is the accepted life expectancy
OR DOT (9 tunnels)—100 years
VA CBBT (2 tunnels)—Depends on the amount of maintenance performed

61. Do you have any additional suggestions and thoughts on the design for fire emergency?
PA DOT (2 tunnels)—see T-20's work
NY/NJ Port Authority—Not at this time

62. Please identify any research that you would like to see performed to help in the implementation of fire safety systems.
PA DOT (2 tunnels)—see T-20's work
MD (2 tunnels)—Dirt build up in the fresh air supply ducts. When fans moved to high for testing or during fires the dirt/dust gets blown up. This resembles smoke on CCTV images and it reduces visibility. It is unknown if this causes other concerns for either the public or emergency responders.
OR DOT (9 tunnels)—We need a national design fire size, duration, and heat rating.
NY/NJ Port Authority—Implementation of a Foam Delivery System

Section 6 Operation, Maintenance, Repair, Rehabilitation

63. What types of exercises and other training are provided to staff and first responders to ensure proficiency in response to an incident and how is the training evaluated?
VA DOT (7 tunnels)—Emergency response manuals are posted in each tunnel's control room and staff are expected to be familiar with the manuals.
PA DOT (2 tunnels)—Yearly review with first responders
MD (2 tunnels)—Quarterly meetings with local fire department, Authority Police and Authority Maintenance Operations staff.
OR DOT (9 tunnels)—ODOT has an emergency drill every two years for first responders.
NY/NJ Port Authority—Bi-annual fire response simulation in the tunnel
VA CBBT (2 tunnels)—Monthly safety meetings
CA DOT (6 tunnels)—No formal tunnel fire training; department staff are required to adhere to requirements of department safety manual and procedures.
WA DOT (2 tunnels)—Very little

64. Would you need additional training tools for operators to manage a fire?
Tunnel fire/systems simulator—19
No—11
Other (please explain)—0

65. What equipment and materials are pre-positioned for response and recovery to a fire, such as for the quick removal of disabled vehicles?
VA DOT (7 tunnels)—Wreckers equipped with materials to contain spills.
PA DOT (1 tunnel)—Tow trucks on site
PA DOT (1 tunnel)—None
MD (2 tunnels)—Tow vehicles are present on site. Fire extinguishers.
OR DOT (9 tunnels)—None
NY/NJ Port Authority—Equipped emergency response vehicle and towing vehicles
VA CBBT (2 tunnels)—Wreckers and fire trucks are at the end of each tunnel
CA DOT (5 tunnels)—1. fire extinguishers; 2. operations center monitors CCTV
CA DOT (1 tunnel)—None
WA DOT (2 tunnels)—Incident response trucks for removal of debris and disabled vehicles.

66. What is considered an acceptable response time?
VA DOT (7 tunnels)—10–15 minutes
PA DOT (1 tunnel)—<3 min tow truck, <10 min EMS
PA DOT (1 tunnel)—less than 5 min, EMS less than 10 min
MD (2 tunnels)—3–5 minutes
OR DOT (9 tunnels)—20 minutes
VA CBBT (2 tunnels)—5 minutes
WA DOT (2 tunnels)—3–5 minutes

67. How often are tunnels and emergency response equipment inspected and tested?
PA DOT (1 tunnel)—Daily
MD (2 tunnels)—Quarterly

VA CBBT (2 tunnels)—Once every 8 hours
CA DOT (6 tunnels)—CO monitors—yearly; fire standpipes—5 years
WA DOT (2 tunnels)—Varies depending on the equipment. Could be weekly or yearly or 5 years for structural items.

68. What methods are used to inspect the structural integrity of the tunnel structure both routinely and after a fire? What materials are used to repair concrete after a fire?

VA DOT (7 tunnels)—Visual inspection and sounding. Concrete is typically repaired with higher strength concrete.
PA DOT (2 tunnel)—a) bridge inspectors are called to use techniques used during a bridge inspection. b) concrete; shotcrete
MD (2 tunnels)—Tunnels are inspected annually as part of our facility inspection program and are inspected by our structural engineers immediately following a fire.
OR DOT (9 tunnels)—Sounding
VA CBBT (2 tunnels)—Consultant engineers inspect the tunnels every year. We have not had to repair any fire damage.
CA DOT (6 tunnels)—Structural inspection 2 years with visual inspection

69. If you were to start a new tunnel project, what key elements would you incorporate in the design and construction to aid you in tunnel fire incident management?

VA DOT (6 tunnels)—Sprinkler system and automatic fire detection system.
PA DOT (1 tunnel)—Nothing: fire department EMS response time under 10 minutes
PA DOT (1 tunnel)—Nothing: we have fire depts. very close to our tunnels that can respond in 5 to 10 min.
MD (2 tunnels)—All required elements from NFPA 502. Control systems to automate fire pattern implementation. CCTV or other fire spread detection in fresh air duct, sump pits, and exhaust air ducts. Public communications system (FM broadcast, PA system, electronic signs, or other means) to instruct the public caught behind the incident.
OR DOT (9 tunnels)—Detection equipment and video surveillance
CA DOT (6 tunnels)—in accordance with NFPA 502 and AHJ
WA DOT (2 tunnels)—Mandatory fire system simulator and monthly training for operations staff.

70. Are the lighting and emergency communication system designed to survive major fire events?

Yes—11
No (please explain how to ensure safe evacuation during an incident that involves major fires)—17
Other (Please explain)—2

71. What are the operational protocols for the use of the ventilation system during a fire event?

VA DOT (7 tunnels)—Control room personnel identify location of fire (using touch screen) and emergency ventilation modes are activated accordingly.
PA DOT (1 tunnel)—All fans are to be run on high speed until directed otherwise by fire & rescue.
MD (2 tunnels)—The current control systems have been programmed with fire-response plans that automate the implementation of fire patterns. Operators can focus on coordinating the manpower using the CCTV to provide situational awareness and immediately develop scope and scale needs for the emergency response. Operators also can access the regional ITS to implement appropriate traffic controls and warnings.
VA CBBT (2 tunnels)—Operations at the incident give requirements at the ventilation building for each incident
CA DOT (6 tunnel)—automatic operation based on CO exposure limits with emergency override by responding AHJ
WA DOT (2 tunnels)—Fans will ramp up to draw smoke and heat away from roadway.

72. How are the maintenance considerations worked into the design elements of tunnel fire detection and fire suppression systems?

PA DOT (1 tunnel)—Controls are put in an accessible area.
MD (2 tunnels)—Detections systems focus on traffic flow. Fires in the roadway always impact traffic and video based analytics detect abnormal traffic conditions within seconds. We have found smoke detection analytics to false alarm too much. Keeping false alarm rates low (below 30–40%) of total alarms is a must to maintain operator trust and involvement. Fire suppression systems are accessible for maintenance inspection and utilize heat systems to address freezing issues.
CA DOT (6 tunnels)—There must be access for maintenance
WA DOT (2 tunnels)—Through a collaborative process between Maintenance and Design offices

73. Do you actively screen or otherwise monitor truck cargoes entering the tunnel without disrupting the traffic flow?

Yes—15
No—15
Other (Please explain)—0

74. What dangerous cargo is acceptable and how is this enforced?

VA DOT (7 tunnels)—Voluntary inspections based on truck placard information

MD (2 tunnels)—Propane tanks 20 lb or larger are not allowed. Gasoline tankers are not allowed. Police monitor and enforce with tickets.
OR DOT (8 tunnels)—Unrestricted. Signs are in place and restrictions are posted on the ODOT web page. Law enforcement monitors occasionally.
OR DOT (1 tunnel)—Flammable cargo is not allowed in the Vista Ridge Tunnels.
VA CBBT (2 tunnels)—No dangerous cargo is permitted.
CA DOT (6 tunnels)—Traffic laws are required to enforce vehicle restrictions
WA DOT (2 tunnels)—All cargo

75. What systems do you have plans for repair or replacement of fire or life safety equipment? (Please check all that apply.)
Tunnel ventilation—8
Fire suppression—0
Standpipes—8
Fire detection—0
Communication—8
Emergency lighting—6
Other (Please explain)—0

Section 7 Follow-up

76. Please provide any additional information or suggestions you may have.
PA DOT (2 tunnels)—Please see info from AASHTO T-20 including the 2005 European Tunnel Scan and the 2009 Domestic Tunnel Scan
CA DOT (3 tunnels)—Gasoline Tankers—freely only from (3 a.m.–5 a.m.)

The last 2 questions were used so that the researchers could contact the respondent for additional information, if necessary.

PART 2: INTERNATIONAL DATA

Section 1 Background Information

The first 15 questions were used so that the researchers could contact the respondent for additional information, if necessary. All this information is shown below.

Section 2 General Information

Questions 16 and 17 were used to obtain the agency name and the name of the tunnels, respectively. All this information is shown below.

18. What year was the tunnel built or expected date of completion?
See chart below

19. Is the tunnel under supervision?
Yes, 24 hr—7
Yes, except at night—0
No—0

20. What is the normal traffic operation?
Uni-directional—6
Bi-directional—1

21. When does the tunnel operate in bi-directional mode? (Please check all that apply.)
Normally—2
At night time—0
Off peak hours—0
Occasionally—0
During Construction/Maintenance in Other tube—0
Never—4
Other (Please explain)—0

Tunnel agency name	No. of surveys submitted	No. of tunnels	Year tunnel was built
Korea Expressway Corporation (Korea)	2	1) Jookryung 2) Average data for 280 (555 tubes) tunnels	1) 2001 2) From 1970 till present
Mak Hungary (Hungary)	1	M6 South	Completed in March 2010
Ministère des transports du Québec (Canada)	1	Ville-Marie & Lafontaine	1976 and 1967
Swedish Road Administration	1	Gota Tunnel	2006
Sydney Harbour Tunnel Company (Australia)	1	Sydney Harbour Tunnel	1992
Vägverket (Sweden)	1	Södra Länken	2004

22. **What type of vehicles use the tunnel? (Please check all that apply.)**
Cars—7
Buses—7
Trucks—7
HGV—5
Special Trucks (military)—3
Gasoline Tankers: freely—4
Gasoline Tankers: supervised when tunnel is closed for normal traffic—0
Other Vehicles—1

Section 3 Fire Incidents Information

23. **How many annual vehicle fire incidents happen in this tunnel (average)?**
No occurrence (Skip questions 9–18)—1
Happened once in lifetime—0
Less than one every year—2
From 1 to 2 every year—2
From 2 to 5 every year—0
Happens at least once a month—0

24. **What were the most severe vehicle fire incidents in this tunnel? (Please check all that apply.)**
Motorcycles fire—0
Passenger car fire—2
Multiple passenger cars (2–4 vehicles)—0
Vans—0
Bus—0
Heavy goods truck fire—3
Multiple trucks fire—0
Tanker fire—0
Alternative fuel vehicle—0
Other—0

25. **Was there any damage made to this tunnel as a result of the fire incident?**
No damages. No impact on tunnel operation—0
No damages. Tunnel was closed for operation for 30 min or more—1
Minor damages (no structural damage)—3
Structural damage which required tunnel closure for an extended period of time—1

26. **Were there any casualties from the fire?**
None—4
Minor—0
Major—1

27. **Has the fire department ever been involved in fire fighting in this tunnel?**
Never—0
Occasionally—1
Every time—4

28. **Was there an investigation performed after the fire?**
Every time—3
Occasionally, depending on fire size—1
Never—0
Once (Please explain when)—1

29. **What was the estimated maximum fire size?**
Swedish Road Administration: Sweden—8 MW
Korea Expressway Corporation (280 tunnels): South Korea—1 to 57 MW
Ministère des transports du Québec (1 tunnel, 2 bores):
Canada—20 MW
Sydney Harbour Tunnel Company: Australia—3 MW

30. **What was the longest duration of the fire?**
Vägverket: Sweden—20 min
Korea Expressway Corporation (280 tunnels): South Korea—120 min
Korea Expressway Corporation (1 tunnel): South Korea—25 min
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—30 min
Sydney Harbour Tunnel Company: Australia—10 min

31. **Have you videotaped any car fire incidence?**
Vägverket: Sweden—No
Korea Expressway Corporation (280 tunnels): South Korea—Yes
Korea Expressway Corporation (1 tunnel): South Korea—Yes
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—Yes
Sydney Harbour Tunnel Company: Australia—Yes

32. **Can you share the video information?**

33. **Has your agency been successful in managing the fire event? (Please provide an explanation.)**
No—0
Yes—5
Partially—0

34. **Do you have an emergency response plan in place?**
Yes—6

35. **Please explain what are the strengths of your agency's fire management program?**
Korea Expressway Corporation (280 tunnels): South Korea
1. Manualized procedure
2. Skilled with fire drill
3. Feedback from design and construction

Korea Expressway Corporation (1 tunnel): South Korea—
1. Manualized procedure
2. Skilled with fire drill
3. Feedback from design and construction

Ministère des transports du Québec (1 tunnel, 2 bores): Canada—Frequent fire simulation and proximity of firefighters

Sydney Harbour Tunnel Company: Australia—Immediate use of a deluge system if required

36. What barriers or difficulties have you or your organization encountered in implementing fire management? (Please check all that apply.)

Technical (please explain)—0
Political (please explain)—1
Legal (please explain)—0
Organizational/institutional (please explain)—1
Staffing/resources (please explain)—1
Other (please explain)—0
None—2

37. What are your suggestions on how these barriers can be overcome?

Mak Hungary: Hungary—We installed fire detection in the new tunnels with direct lines to the Fire Brigade and installed fire hydrants every 100 m.

Korea Expressway Corporation (1 tunnel): South Korea—
Monitoring HGVs
Vehicle maintenance
Installing smoke extraction
Escape route

Ministère des transports du Québec (1 tunnel, 2 bores): Canada—Frequent training and debriefing.

Sydney Harbour Tunnel Company: Australia—Blunt meetings

Section 4 Fire Detection, Fire Protection, Communication

38. What kind of fire detection system does the tunnel have? (Please check all that applies.)

Heat Detection (linear)—5
Heat Detection (other than linear)—2
Smoke Detection—3
Pull Station—0
CCTV—6
Video surveillance technology—3
Phones—7
Other (Please explain)—4

39. What kind of fire protection system does the tunnel have? (Please check all that apply.)

Fire Hydrants along the tunnel—5
Standpipe system with fire hose connections (dry or wet)—2
Fire extinguishers in the tunnel—6
Fire sprinkler system—3
Foam system—1
Fire apparatus in the tunnel—1

40. What kind of fire life safety system does this tunnel have? (Please check all that apply.)

Tunnel ventilation—7
Emergency egress—6
Egress pressurization—3
Other (Please explain)—2

41. What communication systems are used by rescue personnel and others for fire emergency?

Swedish Road Administration: Sweden—Emergency phones and loudspeakers

Vägverket: Sweden—Radio and cell phones

Mak Hungary: Hungary—Wall telephones every 100 m

Korea Expressway Corporation (280 tunnels): South Korea—Radio repeater

Korea Expressway Corporation (1 tunnel): South Korea—Radio repeater

Ministère des transports du Québec (1 tunnel, 2 bores): Canada—Radio

Sydney Harbour Tunnel Company: Australia—Radio and fire phones

42. Please explain how quickly your agency is able to detect and clear routine traffic crashes inside this tunnel?

Swedish Road Administration: Sweden—Our CCTV detects stopped vehicle in 30 seconds and our assistance car or fire department are on place in 10 minutes

Vägverket: Sweden—Detect in minutes. Cleared in 30 min or 60 if there are injuries

Mak Hungary: Hungary—2 min

Korea Expressway Corporation (280 tunnels): South Korea—Detect in 2.2 min and clear in 54 min

Korea Expressway Corporation (1 tunnel): South Korea—Average detection time: 2.2 min

Average time to arrive at site: 8.7 min

Ministère des transports du Québec (1 tunnel, 2 bores): Canada—15 min

Sydney Harbour Tunnel Company: Australia—within 10 min

43. Do you have tow trucks in your agency or do you contract out for theses services?

Have tow trucks—0
Contract out for tow trucks—6
Other (Please explain)—0

44. Are you concerned that your tunnel may not have an adequate fire/life safety system to manage a significant fire event? Please explain.

Vägverket: Sweden—The problem is with congested traffic. The fire safety design is based on a fire flow traffic, which travels faster than the smoke. When there's risk of congestion, the tunnel entry will shut down.

Korea Expressway Corporation (280 tunnels): South Korea—Little concern with hardware. Software and skilled staff in charge is more important.

Sydney Harbour Tunnel Company: Australia—No

Section 5 Design

45. Does your agency have their own standard for tunnel design and for Fire Rating?

Yes—4
No—3
Other (Please explain)—0

46. What guidance and standards are provided to designers to address the fire design issues for new and for retrofitted tunnels? (Please check all that apply.)

NFPA 502—1
ASHRAE—0
FHWA—0
Other (Please explain)—5 (Tunnel04, European Union, domestic regulation, PIARC)

47. Do you specify the design fire size and fire curve to the designers? (Please check all that apply.)

Fire Size—4
Fire Curve—3
Required to follow the NFPA 502—1
Leave it up to the Consultant—2
Leave it up to the Authority Having Jurisdiction (AHJ)—2
Other (Please explain)—1 (Risk Analysis)

48. Is security blast design included in the requirements? (Please check all that apply.)

Security—2
Blast Design—1
Security and Blast Design—2

49. Who is the Authority Having Jurisdiction (AHJ)?

Our agency—1
Fire department—3
Don't know—0
Other (Please explain)—2

50. Do you apply a risk assessment approach for fire engineering?

Yes—7
No—0
Other (Please explain)—0

51. How do you handle specific risk that cannot be mitigated?

Vägverket: Sweden—Improve the safety measures, such as distance between exits, FFFS, traffic control, etc.

Korea Expressway Corporation (280 tunnels): South Korea—Main goal is to minimize specific risk such as chemical tanker leak or explosive material.

Korea Expressway Corporation (1 tunnel): South Korea—Main goal is to minimize specific risk such as chemical tanker leak or explosive material.

Ministère des transports du Québec (1 tunnel, 2 bores): Canada—When we can we eliminate the risk at the source; otherwise, we try to mitigate by being prepared to intervene optimally.

Sydney Harbour Tunnel Company: Australia—Vigilance

52. What traffic management and safety innovations are deployed or planned to minimize or eliminate problems such as congestion and traffic management during a fire?

Vägverket: Sweden—The tunnel entrances are shut automatically, ramp metering are reducing traffic at the surface to let the cars leave the tunnel as quickly as possible.

Korea Expressway Corporation (280 tunnels): South Korea—Entrance shut equipment, Lane control system, Variable messaging sign by Patrol personnel Korea Expressway Corporation (1 tunnel): South Korea—Entrance suspension equipment, Lane control system, Variable messaging sign control by patrol car

Ministère des transports du Québec (1 tunnel, 2 bores): Canada—ITS, detection, and communications equipment

Sydney Harbour Tunnel Company: Australia—Vigilance Waterscreen displaying a 7 × 4.5 m stop sign

53. Do you have an emergency response plan in place?

Yes—5
No—0
Other (Please explain)—2

54. Which agency has the role of incident commander?

Vägverket: Sweden—fire brigade

Mak Hungary: Hungary—fire brigade

Korea Expressway Corporation (280 tunnels): South Korea—In cooperation with fire department

Korea Expressway Corporation (1 tunnel): South Korea—In cooperation with fire department
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—Firefighters
Sydney Harbour Tunnel Company: Australia—Fire brigade once on site

55. What best practices can you share in the areas of prevention, mitigation, and recovery from fire incidence?
Korea Expressway Corporation (280 tunnels): South Korea—From the case of Dalsung Tunnel accident, which is explosion of missile propellant.
Korea Expressway Corporation (1 tunnel): South Korea—Explosion of missile projectile case in Dalsung Tunnel
>20 hours to re-open
>3 month to full recovery
Sydney Harbour Tunnel Company: Australia—
Video smoke detection.
Alert operators
Deluge system

56. Would you consider protection of the tunnel with the fixed fire suppression system (sprinkler system) to meet the new NFPA 502 Max Fire Heat Release Rate Requirements, if proven effective?
Yes—4
No—2
Other (Please explain)—0

57. Have you identified gaps in research and design for tunnel fire safety, or fire detection and protection?
No—2
Yes (Please explain)—4

58. Can you suggest strategies to eliminate the gaps and improve tunnel fire safety?
Vägverket: Sweden—More research to develop the installations in a more cost-effective way
Korea Expressway Corporation (1 tunnel): South Korea—
Promotion (PR)
Accident prevention
Improvement of facilities
Sydney Harbour Tunnel Company: Australia—Closer ties to other operators

59. Would you consider a fire event to be similar to a seismic event for design purposes? (Example design for the fire event which has a high probability to happen once in 500 years or 2,500 years?)
Yes—0
No—5
Other (Please explain)—1

60. What is this tunnel life's expectancy?
Swedish Road Administration—80 years
Vägverket: Sweden—100 years
Mak Hungary: Hungary—200 years
Korea Expressway Corporation (280 tunnels): South Korea—50 to 100 years
Korea Expressway Corporation (1 tunnel): South Korea—50 to 100 years
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—100 years
Sydney Harbour Tunnel Company: Australia—100 years

61. Do you have any additional suggestions and thoughts on the design for fire emergency?
Vägverket: Sweden—There are 100 m between the emergency exits. The fire brigade can use these to reach an accident and never have to take the risk of entering the burning tunnel with their vehicles.
Korea Expressway Corporation (1 tunnel): South Korea—Equipping extinguisher and respirator should be forced by law

62. Please identify any research that you would like to see performed to help in the implementation of fire safety systems.
Vägverket: Sweden—More research to develop the installations in a more cost-effective way

Section 6 Operation, Maintenance, Repair, Rehabilitation

63. What types of exercises and other training are provided to staff and first responders to ensure proficiency in response to an incident and how is the training evaluated?
Vägverket: Sweden—The staff of the traffic command centre have annual exercises to handle a large accident. The personnel in the incident response vehicles have a full fire fighter training and annual exercises.
Korea Expressway Corporation (1 tunnel): South Korea—Annual fire drill with fire department by manual, technical education, spot check, real fire case evaluation
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—Ventilation test with fire and smoke
Sydney Harbour Tunnel Company: Australia—We burn cars in the tunnel to demonstrate the smoke, heat, and noise to our operators. This also enables the deluge and ventilation to be proven. All operators have to complete task books on a regular basis.

64. Would you need additional training tools for operators to manage a fire?

Tunnel Fire/Systems Simulator—4
No—2
Other (please explain)—1

65. What equipment and materials are pre-positioned for response and recovery to a fire, such as for the quick removal of disabled vehicles?

Vägverket: Sweden—The incident response vehicles are positioned so that they can reach any part of the tunnel system within 5 minutes 24-7. The tow trucks have a quick response time.
Mak Hungary: Hungary—The fire brigade has their own container full of rescue equipment
Korea Expressway Corporation (1 tunnel): South Korea—Special equipment to tow for special trucks
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—Towing trucks
Sydney Harbour Tunnel Company: Australia—Two tow trucks during peak periods

66. What is considered an acceptable response time?

Swedish Road Administration—10 min
Vägverket: Sweden—5 min
Korea Expressway Corporation (280 tunnels): South Korea—10 to 15 min
Korea Expressway Corporation (1 tunnel): South Korea—10 to 15 min
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—7 min
Sydney Harbour Tunnel Company: Australia—Less than 2 min

67. How often are tunnels and emergency response equipment inspected and tested?

Swedish Road Administration—Depends
Vägverket: Sweden—Annually
Korea Expressway Corporation (280 tunnels): South Korea—At least once a month
Korea Expressway Corporation (1 tunnel): South Korea—At least once a month
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—2 times a year
Sydney Harbour Tunnel Company: Australia—Every 6 months

68. What methods are used to inspect the structural integrity of the tunnel structure both routinely and after a fire? What materials are used to repair concrete after a fire?

Vägverket: Sweden—The road authority provides specialists after an incident. There are maintenance done in the tunnels every month, and the tunnel structures are checked after a time schedule.
Sydney Harbour Tunnel Company: Australia—Consultants

69. If you were to start a new tunnel project, what key elements would you incorporate in the design and construction to aid you in tunnel fire incident management?

Vägverket: Sweden—Traffic control on the surface around the tunnel, to insure that the traffic can get out of the tunnel system quickly.
Korea Expressway Corporation (1 tunnel): South Korea—smoke extraction in combination with ventilation FFFS
Sydney Harbour Tunnel Company: Australia—Deluge and clear identification of deluge zones

70. Are the lighting and emergency communication system designed to survive major fire events?

Yes—5
No (please explain how to ensure safe evacuation during an incident that involves major fires)—1
Other (Please explain)—0

71. What are the operational protocols for the use of the ventilation system during a fire event?

Vägverket: Sweden—Yes, the ventilation is very important in case of a fire.
Mak Hungary: Hungary—Manual
Korea Expressway Corporation (1 tunnel): South Korea—Keep critical velocity after completion of evacuation downstream of fire
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—Preprogrammed scenarios are operated and depend on the fire location, with regard to the camera seeing the fire
Sydney Harbour Tunnel Company: Australia—Preprogrammed for single fire, multiple fire, and congested tunnel.

72. How are the maintenance considerations worked into the design elements of tunnel fire detection and fire suppression systems?

Vägverket: Sweden—No key parts in the traffic tunnel, as much maintenance as possible should be carried out in technical rooms and emergency exits.
Korea Expressway Corporation (1 tunnel): South Korea—Every result of maintenance, fire drill, and fire accident are considered into design. For example, corrosion problems of metals in the tunnel, false alarm of FFFS, etc.
Sydney Harbour Tunnel Company: Australia—Video smoke detection does not require access

to the tunnel. Cameras must be located at about 60 m intervals

73. Do you actively screen or otherwise monitor truck cargoes entering the tunnel without disrupting the traffic flow?
Yes—1
No—5
Other (Please explain)—0

74. What dangerous cargo is acceptable and how is this enforced?
Vägverket: Sweden—All types of cargo at night, no explosive cargo at daytime.
Korea Expressway Corporation (280 tunnels): South Korea—No restriction
Korea Expressway Corporation (1 tunnel): South Korea—No restriction of material. Only loading method is restricted.
Ministère des transports du Québec (1 tunnel, 2 bores): Canada—
Sydney Harbour Tunnel Company: Australia—None, government agency responsibility

75. What systems do you have plans for repair or replacement of fire or life safety equipment? (Please check all that apply.)
Tunnel ventilation—0
Fire suppression—0
Standpipes—1
Fire detection—0
Communication—0
Emergency lighting—0
Other (Please explain)—0

Section 7 Follow-up

76. Please provide any additional information or suggestions you may have.
Sydney Harbour Tunnel Company: Australia—Provide good training to good operators with the right tools to do the job

The last two questions were used so that the researchers could contact the respondent for additional information, if necessary.

APPENDIX D

Tunnel Safety Projects Additional Description

D.2.4 INTERNATIONAL TECHNOLOGY SCANNING PROGRAM (*2*)

The nine initiatives and practices listed below relate to human factors, planning, design, and incident and asset management.

1. Develop Universal, Consistent, and More Effective Visual, Audible, and Tactile Signs for Escape Routes.

   The scan team noted that the signs Europeans use to indicate emergency escape routes are consistent and uniform from country to country. Emergency escape routes are indicated by a sign showing a white-colored running figure on a green background. Other signs that indicate the direction (and distance in meters) to the nearest emergency exit also have the white figure on a green background, as used in European buildings and airports. All SOS stations in the tunnels were identified by the color orange. This widespread uniformity promotes understanding by all people and helps assure that in the event of an emergency, any confusion related to the location of the emergency exit will be minimized. In addition, the team learned that combining the use of sound that emanates from the sign, such as a sound alternating with a simple verbal message (e.g., "Exit Here") with visual (and, where possible, tactile) cues, makes the sign much more effective.

   The U.S. tunnel engineering community relies on National Fire Protection Association (NFPA) 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, and NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, for fire protection and fire life safety design standards. These standards need to incorporate the most current technology and results of recent human response studies on identification and design of escape portals, escape routes, and cross passages.

2. Develop AASHTO Guidelines for Existing and New Tunnels

   Single-source guidelines for planning, design, construction, maintenance, and inspection of roads and bridges have been in place for many years. NFPA has developed standards for safety in highway tunnels and passenger rail tunnels. The American Public Transportation Association (APTA) has general safety standards and guidelines for passenger rail operations and maintenance that incorporates some of the NFPA standards by reference. However, AASHTO does not have standards or guidelines specifically for highway or passenger and freight rail tunnels. Recently, the AASHTO Subcommittee on Bridges and Structures created a new committee, the Technical Committee on Tunnels (T-20), to help address this problem. T-20 takes the lead in developing AASHTO standards and guidelines for existing and new tunnels, working with NFPA, APTA, FHWA, and the appropriate TRB committees on standards and guidelines for highway and passenger and freight rail tunnels. Tunnel safety measures such as the Mont Blanc Tunnel emergency pull-out area and variable message sign showing maximum speed limit and required vehicle spacing, as well as refuge room requirements require considerations.

3. Conduct Research and Develop Guidelines on Tunnel Emergency Management that Includes Human Factors

   Tunnel design solutions may not anticipate human behavior. Consistently predicting the way people will behave in an incident is difficult. During emergency situations, human behavior is even harder to predict as the stress of the situation replaces intellect with curiosity, fear, or even panic. During a tunnel emergency, people often must be their own first rescuers and must react correctly within a few minutes to survive. Tunnel emergency management scenarios and procedures must take human behavior into account to be fully effective in saving lives. The European experience in human factor design provides a good basis for the United States to discover and include more effective measures for tunnel planning, design, and emergency response.

4. Develop Education for Motorist Response to Tunnel Incidents

   During an emergency situation, most people do not immediately know what to do to save themselves and others. Motorists are their own first rescuers and European studies indicate that self-rescue may be the best first response for a tunnel incident. For this to be an effective strategy, it is important to educate the public about the importance of reacting quickly and correctly to a tunnel incident, such as a fire.

5. Evaluate Effectiveness of Automatic Incident Detection Systems and Intelligent Video for Tunnels

   The scan team learned of sophisticated software that, using a computer system interfacing with ordinary video surveillance cameras, automatically detects tracks and records incidents. As it does so, it signals the operator to observe the event in question and allows the operator the opportunity to take the appropriate action. This concept can also be applied to detect other activities and incidents in areas besides tunnels, including terrorist activities, crashes, vandalism and other crimes, fires, and vehicle breakdowns.

6. Develop Tunnel Facility Design Criteria to Promote Optimal Driver Performance and Response to Incidents

The Europeans found that innovative tunnel design that includes improved geometry or more pleasing visual appearance will enhance driver safety, performance, and traffic operation. For example, the full-size model of one section of the twin roadway tube for the A-86 motorway in Paris demonstrates the effectiveness of good lighting and painting to improve motorist safety. It is a particularly important consideration for a tunnel roadway section designed with limited headroom.

7. Investigate One-Button Systems to Initiate Emergency Response and Automated Sensor Systems to Determine Response

The European scan revealed that one of the most important considerations in responding to an incident is to take action immediately. For this to be effective, the operator must initiate several actions simultaneously. An example of how this immediate action is accomplished is the "press one button" solution that initiates several critical actions without giving the operator the chance to omit an important step or perform an action out of order. From the Mont Blanc Tunnel operations center control panel, operators can initiate several actions by moving a yellow line over the area where a fire incident is indicated on a computer screen. This "one-button" action reduces the need for time-consuming emergency decisions about ventilation control and operational procedures.

The Europeans observed that tunnel operations personnel have difficulty keeping up with events like tunnel fires. They believe that an automatic system using devices like opacity sensors can help determine the correct response. A closed-loop data collection and analysis system that takes atmospheric conditions, tunnel air speed, and smoke density into account may best control fans and vents.

8. Use Risk-Management Approach to Tunnel Safety Inspection and Maintenance

The scan team learned that some organizations use a risk-based schedule for safety inspection and maintenance. Through knowledge of the systems and the structure gained from intelligent monitoring and analysis of the collected data, the owner can use a risk-based approach to schedule the time and frequency of inspections and establish priorities. It makes more sense to inspect less critical or more durable portions of the system on a less frequent basis and, instead, concentrate inspection efforts on the more critical or more fragile components. A risk-based assessment of the condition of facilities also can be used to make optimal decisions on the scope and timing of facility maintenance or rehabilitation. This method offers a statistical process to manage the tunnel assets.

9. Implement Light-Emitting Diode Lighting for Safe Vehicle Distance and Edge Delineation in Tunnels

The scan team noted that in several European tunnels, light-emitting diode (LED) lights were installed along the edge of the tunnel at regular intervals of approximately 10 to 20 meters (m), or 33 to 66 feet (ft), to clearly identify the edge of the roadway. These lights were either white or a highly visible yellow color. In some tunnels, there were blue lights at 150 m (490 ft) intervals spaced among these edge-delineation lights. Motorists are instructed through formal (for truck and bus drivers) and informal driver education to keep a safe distance between them and the vehicle in front, and that distance is indicated by the spacing of the blue lights. This visual cue is more reliable than asking motorists to establish distance between vehicles using speed based guidelines, such as maintaining one car length spacing for every 10 miles per hour (16 kilometers per hour) of speed. The LED markers are also less susceptible to loss of visibility because of road grime and smoke during a tunnel fire.

D.2.5 UPTUN (*8*)

WP1. This work package assesses monitoring and detection systems installed at present, assessed if improvements to those systems could be made, evaluate new methods and techniques for determining incidents and fires inside and outside tunnels. In order to ensure that the ultimate results of UPTUN are achieved it was necessary to make a detailed database of all road tunnels in Europe, detailing the type of tunnels in each country, what types of detection systems are in place, whether any suppression systems are installed, and details of recent incidents. This database was used to analyze these recent incidents and to assess if tunnels that have better monitoring and detection systems achieved a quicker response to an incident, which would reduce the impact of an incident and minimize the economic impact in the surrounding areas.

WP1 Technical tasks:

1.1 Categorization and listing of European tunnels.

1.2 Causes and prevention of accidents and fire.

1.3 Existing detection and monitoring systems.
1.4 Exploration of alternative or new technology for detection of moving fires, detection of fires outside tunnels, detection of the migration of fires.
1.5 Implementation of proposed solutions and prototypes.

WP1 Objectives:

- To categorize European tunnels.
- To identify probabilities of incidents potentially leading to fires and propose, investigate and promote methods to reduce these.
- To list potential suitable existing detection and monitoring techniques and to investigate reliability of existing systems.
- To develop innovative measures to detect the fire load and growth.

Small-scale tests were performed to evaluate the new systems with regard to reliability, accuracy, fire resistance, and so forth.

WP2. (*78*) WP 2 aims primarily at developing cost-efficient mitigation measures when a fire occurs in a tunnel. The focus of the work package is therefore an existing and innovative mitigating system. In support of this objective, it aims at improving the necessary evaluation tools and at providing innovative new tools where appropriate. Specifically envisaged tools are the mathematical models and the appropriate design scenarios that enable the prediction of hazard conditions. The appropriate design shall be based on statistical data and laboratory-scale tests. By providing better knowledge about the fire and explosion hazards involved, design fire scenarios and acceptance criteria were to be developed.

WP2 Technical tasks:
2.1 Development of realistic design scenarios
2.2 Define acceptance criteria (*79*).
2.3 Evaluation of existing tunnels and current technology (*80*).
2.4 Develop new innovative technologies (*81*).
2.5 Engineering guidance and implementation (*82, 83*).

WP2 Objectives:

- To provide design fires. Design fires will be used to measure the efficiency of all mitigation systems. Acceptance criteria for fire effluence in the tunnel shall be suggested to provide a necessary level of safety to be achieved by mitigation technologies.
- Establish knowledge about the performance of current technologies and to provide a path for development and verification for innovative technologies.
- To improve and to verify the efficiency of innovative fire mitigation systems in tunnels, both as stand alone systems and in combinations with other systems. Focus shall be given to cost-efficiency.
- Identify parameters affecting the effect of mitigation and to provide guidance on how to design a reliable mitigation system and to predict the resulting achievements.
- Results of the study were summarized in the paper by Haukur Ingason of SP Swedish National Testing and Research Institute “DESIGN FIRES IN TUNNELS” referenced and further discussed in this report (*28*).

WP3. The main objective of WP3 was to find, develop, evaluate, and promote new methods and means to remove, neutralize or correctly assess all factors that contribute to a negative human response in incidents (larger accidents always resulted from smaller incidents) and accidents (resulting if no adequate action is taken).

WP3 Technical tasks:
3.1 Review of state of the art and interrelation with other projects.
3.2 Response of the end-user.
3.3 Tunnel operator.
3.4 Emergency response teams.

WP3 Objectives:

- Knowledge will be collected on the design and safety measures in current European tunnels.
- This task focuses on how information is presented, how long it takes before tunnel users actually understand the situation (depending on specific scenario and the information provided), and how they choose their escape route.
- This task will focus on an analysis of the task of the operator: how operators gain information, what makes them miss some incidents, how the operators come to a decision, what way can they be supported, how the operators handle the occurrence of several incidents within a short period of time, and how the operators communicate with the emergency rescue teams.

It seems important to discuss some results of this work group for the benefits of agencies and operators. Simultaneous management of the problem is required in order to guarantee effective and on-time intervention of operators. The response teams get their information from the tunnel operator (or from the individual tunnel users) and have to form an idea of the seriousness of the incident, the actions they have to take, the number of people that have to be involved, followed by having to instruct their team members to work together. Furthermore, the tunnel operators may also help the emergency response teams by providing proper information.

The tunnel operator has an important role to react to a tunnel incident in a timely manner. The operator needs to stand-by in order to detect any incidents happening, to decide what the proper action to take is, and needs to provide other people with information (road users, emergency services, other operators, and so forth). The role of the operator is extremely important (overview of the situation, possibilities to communicate to several services, and so forth).

In the UPTUN project, an analysis was done of operator tasks and bottlenecks based on literature reviews, a Dutch tunnel safety review, and operators interviews. The tasks identified were:

- Monitoring the traffic flow and situation in the tunnel (and vicinity) using cameras, sensor readings, and communication equipment. Constant vigilance was required.
- Preparation for effect reduction: education, training, exercises.
- Fast and correct detection of any event or disturbance likely to escalate into an incident.
- Closing the tunnel; switching equipment to "emergency mode" (lights, ventilation, speed limits, escape doors, and so forth).
- Alerting other operators (where applicable), rescue services, and tunnel users (instructing them for escape if necessary).
- Communicating with tunnel users to help them escape and to help them assist others or correct the situation (such as, extinguishing a small fire).
- From the control room, assisting the rescue services in their rescue operation.
- Evaluating and registering the incident.

The main factors that have a substantial effect on task performance and mental effort of the operator are:

1. Percentage time occupied: the percentage of available time that the operator is occupied with his or her tasks. The higher this percentage is, the higher the cognitive load.
2. Level of information processing: relates to the complexity of tasks.
3. Number of task-set switches: refers to the number of switches the operator has to make between different task-sets. The more switches, the higher the cognitive load.

The operator overload can occur when the operator does not have enough time to finish the tasks, the operator tasks are too complicated, or the operator has to perform too many tasks at the same time (or a combination of any of these elements). An underload, just as overload, may lead to suboptimal performance. Ideally, the task load matches the operator's mental capacity in a certain task setting. Other identified bottlenecks (although this list does not include all bottlenecks identified) were:

- Vigilance problems during long periods of normal operation (related to underload).
- Unclear allocation of responsibilities and authority to personnel.
- Insufficient skills due to lack of practice exercises, especially with the rescue services.
- Overdue, incorrect, or incomplete detection of incident due to the combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
- Too many incoming signals, not all of which are relevant at this time (related to overload).
- Absence of or insufficient coordinated procedures between operators and rescue services.
- Absence of adequate incident evaluating and registration procedures.
- Mistake in incident is not evaluated or registered due to fear for career consequences.

After the tasks and bottlenecks were identified, the next step was to find solutions for the most important bottlenecks and designing an improvement strategy. Using a prioritized list of bottlenecks and general methods for influencing operator behavior generates possible solutions for the most important bottlenecks. Possible solutions can be found in terms of:

- Recruitment (assess the proper criteria).
- Training and exercise (to improve skills, but also to test the affectivity of procedures).
- Personnel and organization (number of people present, working method with time schedules and organizational culture).
- Task support (such as procedures and guidelines).
- Control room and interface design (technical tools, such as one button to indicate a major accident, good tools to instruct the tunnel users).

WP4. The objectives are:

- To optimize the thermal and structural behavior of all tunnel components designed for active and passive safety.
- To increase the robustness and load bearing capacity under accidental conditions.
- To assess the performance of the integral tunnel structure in all fire phase conditions: from ignition, through growth to the fully developed stage and the decay period.
- To achieve a robust working/functioning complete system, including the effects of fire temperatures.
- To reduce and limit non-operational time and repair retrofitting work.
- To evaluate existing technology with main emphasis on cost-benefit (including maintenance).
- To establish safer design and to evaluate recommendations for optimal tunnel systems.

WP4 Technical tasks:

4.1 Structural elements functional performance, and load bearing capacity.
4.2 Improving components functional capacity.
4.3 Innovative damage assessment and repair and recovery and retrofitting.
4.4 Proposal of innovative solutions.
4.5 Safety levels criteria evaluation/engineering guidance and implementation.

WP4 Objectives:

- It is necessary to achieve better understanding and gain more insight in structural performance of concrete load-bearing elements under fire emergency conditions

- To develop new mitigating measures.
- To avoid or limit structural damage to an acceptable level.
- To provide fast repair methods.

By means of numerical analyses and laboratory fire tests, data are established for all individual elements regarding its resistance and functionality as a function of its exposure time. These data help to point out possible improvements to currently available elements and to make recommendations for designing new ones. The different element with the best characteristics is identified and, if appropriate, proposed for use in upgrading tunnels.

Therefore, it is essential to:
- Assess the damage level very quickly.
- Propose and apply adequate repair and recovery methods.

The rather hostile tunnel environment, in combination with the desired limited non-operational time, requires development of innovative FAST and ACCURATE damage assessment techniques. For tunnels where current system design is not suitable, alternative innovative solutions shall be suggested. Alternative optimized configurations and advanced technological engineering solutions shall be studied and verified. Indications on how to achieve reductions and/or elimination of explosive spalling were given.

WP5. This task encapsulates the essence of the UPTUN project; namely, the evaluation and upgrading of the safety level of existing tunnels consistent with the safety levels established in this project as a whole. In that respect, this work package brings together all the various strands from the other work packages and, therefore, inevitably requires input from and collaboration with all the partners of this major project.

WP5 Technical tasks:
5.1 Identifying safety features.
5.2 Setting criteria for evaluating safety levels and systems failure.
5.3 Holistic evaluation and upgrading of existing tunnels safety.
5.4 Example: Upgrading of an existing tunnel.
5.5 Financial, socio-economic, macroeconomic, and environmental evaluation of upgrading tunnels to improve fire safety.

WP5 Objectives:
- To ensure that the safety features are clearly identified in a rational manner.
- To ensure that the evaluation criteria are clearly defined in a rational manner taking into consideration the interaction between the different safety features.
- To develop a procedure called "UPGRADE" for evaluating and upgrading the safety level of a tunnel as a whole and to present the output in terms of risk profiles for both people and the infrastructure. An assessment of fire risk profiles for a tunnel before and after upgrading will then allow the socio-economic impact to be evaluated.
- To demonstrate the practical utility of the evaluating and upgrading procedure by applying it to an existing tunnel.
- To demonstrate the cost-effectiveness of the UPTUN project and assess its wider socio-economic impact.

WP6. Objectives:
- Demonstrate experimentally the effectiveness of the innovative fire safety features in combination.
- Demonstrate, with before and after tests, that the innovative upgrading measures proposed in this project provide major improvements in fire safety when compared with the existing tunnels situation without upgrading.
- Provide feedback to work packages 1 to 4 in terms of the interaction of their individual features with the features developed in other work packages.
- Validate the theoretical model developed in work package 5.
- Make recommendations for upgrading based on actual testing.

WP6 Technical tasks:
6.1 Framework for the demonstrations
6.2 Demonstration before upgrading
6.3 Demonstration after upgrading
6.4 Analysis of results and validation of theoretical model

WP6 Objectives:
- To optimally design full-scale tests that show interaction and validate the models developed in the previous work package.
- To set a reference for identifying the positive effect of the innovative measures or innovative combination of measures by determining the safety level of non-upgraded tunnel(s).
- To investigate the innovative measures in realistic configurations and combinations to determine their actual beneficial effect. To gather validation information for the models developed in the other work packages.
- To provide validation information for the theoretical models. To make recommendations for large scale data gathering and analyses. To provide adequate promotional and educational material.

Furthermore, since not all aspects can be foreseen from the start of the project, nor can all problems be solved within UPTUN, strong links have been established with existing relevant research projects on the national and international level, such as the European projects DARTS, FIT, and SafeT. WP 7 Promotion, dissemination, education/training, and socio-economic impact (WPL STUVA; D)

D.2.6 FIT (*8*)

Technical Report Part 1, *Design Fire Scenarios* (*76*), describes recommendations on design fire scenarios for road, rail, and metro tunnels. Design fires are to cover different relevant scenarios, such as design fires in regard to the evacuation of people and to ventilation purposes, as well as in regard to the structural loads, which are presented and recommended. The report collects data from different countries, including Germany, France, Italy, and the U.K., as well as international organizations, such as PIARC, ITA, and UPTUN. It also incorporates from the experiences in individual tunnels, including Mont Blanc, Tauern, Nihonzaka, Caldecott, and Pfänder. The report includes basic principles of design fires, tunnel fire statistics, and impacts of fires and smoke in tunnels on people, equipment and structure. The data are analyzed and different sets of data are compared to ascertain the degree of confidence attributed to the information.

In Technical Report Part 2, *Fire Safe Design,* a compilation of relevant guidelines, regulations, standards, or current best practices from European member states (and major tunneling countries, like Japan) are given. The analysis is focused on all fire safety elements regarding tunnels and is classified according to the transport nature: road, rail, and metro. The three sections in the report present the collected guidelines and regulations, their analytical abstract, and table of contents. About 50 safety measures are presented and compared related to structural measures (19), safety equipment (36), and structure and equipment with response to fire (3). For each type of measure the impact on safety is presented with a synthesis and a detailed comparison of the comprehensive list of safety measures.

The occurrence of a fire in a tunnel provokes a need for responses from tunnel users, the operators, and the emergency services personnel. Technical Report Part 3, *Fire Response Management,* presents the best practices to ensure a high level of safety.

APPENDIX E
Fire Tests

E-1 Full Scale Tests

E-1.1 Ofenegg Tunnel Tests

Ofenegg Tunnel (Switzerland 1965) (*21*)

These tests were carried out in order to study the ventilation capacities in the case of a fire under the large Swiss tunnel projects of the sixties.

The total cross-sectional area of the Zwenberg and Ofenegg tunnels was approximately 24 m^2 (258 ft^2), which is much smaller than the cross-sectional area of normal road tunnels with two lanes, which is between 45 m^2 (485 ft^2) and 60 m^2 (650 ft^2).

The facility was a railway tunnel with a dead end located 190 m (620 ft) from the portal. About 11 fires were performed using fuel pools from 6.6 m^2 to 95 m^2 (71 ft^2 to 1,023 ft^2). Gasoline was poured into a concrete tub and then ignited. The gasoline used was regular gasoline (86% carbon and 14% hydrogen) with a density of $\rho = 730$ kg/m^3 (at 15°C) or 45.6 lb/ft^3 (at 59°C) and a lower calorific value of approximately 44 MJ/kg (18,917 Btu/lb). The rate of burning of gasoline in free air is a function of the fire area. It first increases as the fire site increases in size and then remains constant when the fire site reaches an area of approximately 1 m^2 (11 ft^2).

The Ofenegg report details a number of tests performed in an abandoned Swiss railway tunnel to investigate the CO concentration, temperature distribution, visibility, response to ventilation, response to sprinklers, effect on tunnel systems and structures, and effect on vehicles and people of several fire sizes as a function of time. Several animal carcasses and vehicles were exposed at various distances to deliberately ignited pans of fuel.

During the 500 L (132 gal) fuel tests, the semi-transverse supply had no mitigating effects, while the longitudinal ventilation "drove the flames torch-like" downwind. During the 500 L (132 gal) sprinkler test, sprinkler droplets initially evaporated into a high-temperature steam cloud, causing more damage than the unsprinklered fires. The open fire was apparently soon extinguished, accompanied by a strong odor of fuel at the portal, but the fire reignited after 17 minutes (status of sprinkler flow unstated) with significant but non-explosive wave-front propagation.

During the 1000 L (264 gal) fuel tests, calculated burning rates were lower than those observed for similarly sized fires in the open. Started immediately after ignition, the sprinklers reduced the maximum ceiling arch temperatures from, but the steam apparently pushed burning gases and gasoline vapors into adjacent tunnel sections, where they continued to burn. The fire was apparently extinguished for 10 minutes, but the tunnel filled with fuel vapors, which exploded in the l9th minute. This caused extensive damage to the test facility injuring three technicians.

All three incidents caused doubt on the effectiveness of sprinklers in containing a fire or in limiting the range and severity of damage

E-1.2 Zwenberg Tunnel Tests

Zwenberg Tunnel (Austria, 1975) (*21*). The ignited fuel areas were 6.8 m^2 (73.2 ft^2) and 13.6 m^2 (146.4 ft^2). The performed measurements were: temperature, gas concentration (CO, CO_2, NO_x, O_2), opacity, and combustion rate.

Tests were commissioned by the Australian Ministry for Construction and Technical Affairs. They were carried out in an abandoned rail tunnel equipped with a fully transverse ventilation system. The investigators attempted to answer the following questions:

- How do conditions in the traffic space differ when applying different patterns of ventilation?
- What improvements can be expected from selected changes to the design, construction, and operation of exhaust air openings?

The test program consisted of 23 tests of a "standard" fire using 200 liters (52.8 gal) of gasoline with a fire area of 6.8 m^2 (73 ft^2), three tests using 400 liters (106 gal) of gasoline with a fire area of 13.6 m^2 (146 ft^2), and four other tests using other fuels. These tests investigated the effect of varying five parameters:

- Location of fresh air injection (high or low).
- Quantity of smoke and fumes exhausted.
- Quantity of fresh air injected.
- Forced longitudinal ventilation in the traffic space.
- Conditions in the traffic space (open or obstructed).

The investigators believe the size of the area affected by the fire and thus the possibilities of escape and rescue depend to a great extent on the pattern of ventilation, more so than on any other parameter. With longitudinal flows of at least 6.5 ft/s (4.4 mph or 7.1 km/h), a "burner effect" was created on the exhaust air side of a fire. The smoke spread at approximately the same rate as the longitudinal flow (for the 200 L fires or

52.8 gal), but even small fires filled long sections of the tunnel on the exhaust side of the fire point with smoke.

They suggest that it is not possible to rescue people on the exhaust air side from the fresh air side. Contrary to the conditions on the exhaust air side, however, a longitudinal flow creates very favorable conditions on the fresh air side of the fire. If the longitudinal flow can be stopped or if none exists from the start, the danger area and the smoke area will be symmetric to the fire point. The tests confirmed that full extraction in connection with throttled fresh air reduces the danger area as well as the smoke area.

Maximum exhaust air temperature reached during the full extraction tests was only 85°C (185°F) and decreased as the fire point approached the fan location. With this dilution, the investigators believe 250°C (482°F) is a sufficiently high temperature criteria for exhaust fans installed in a fully transverse system. This does not agree with actual conditions experienced in the Holland Tunnel and Caldecott fires.

It was concluded that:

- The fans allow for command from the control center to be executed within a very short period of time.
- A fire alarm program for each tunnel specifies in detail the operating pattern of the ventilation system in relation to the location of the fire and other marginal conditions.
- In cases where the control center is equipped with a computer, the individual programs are stored and available to be called off at any time.

Regarding the location of fresh air injection and exhaust openings:

- The overriding recommendation derived from the tests requires throttling of the fresh air supply (or change-over to extraction in case of a reversible semi-transverse system) in case of a fire.
- When the fresh air supply is throttled, the injection "from below" shows no decisive advantage compared with the injection from "above."
- The only conclusion gained during the tests is that the enlargement of the exhaust openings near the fire point has no effect as long as a considerable (6.5 ft/s, 4.4 mile/h, or 7.1 km/h) longitudinal flow passes over the fire point.
- In fully transverse systems, the immediate action must be to get longitudinal flow under control before trying to make further improvements by enlarged exhaust openings.

E-1.3 PWRI Experiments

The Japanese full-scale test program (Japan, 1980) used a 700 m (2,300 ft) long gallery built by the Public Works Research Institute (PWRI) and a 3300 m (10,830 ft) long road tunnel. Sixteen (16) experiments were performed in the gallery and 8 in the tunnel. The fire sources were fuel pools (10 tests with 4 m^2 or 43 ft^2, 2 tests with 6 m^2 or 64.6 ft^2), passenger cars (6 tests), and buses (6 tests). The physical conditions measured in the tunnel during the fires were based on the emergency capabilities. The influence of the longitudinal airflow velocity was tested. Other tests included oversized exhaust ports for smoke removal.

The important results of this investigation were reported as follows:

- Best smoke removal was achieved by operating both east and west fans for extraction regardless of the fire location, with the bulkhead damper fully open.
- Under these conditions, air flowed toward the open dampers by as much as 5 meters per second (11 mph or 17.7 km/h).
- The space between the fire point and the open damper or dampers is filled with smoke.
- The inertial effect of longitudinal air flow is lost within three minutes after fire mode is activated.

E-1.4 Repparfjord Tunnel Tests Near Hammerfest (Norway, 1990–1992) (21)

These experiments were performed in an abandoned 2.3 km (1.4 mile) long mining gallery (rough wall surfaces and cross section varying from 30 to 40 m^2 or 323 to 430.6 ft^2). They gathered nine European countries (these experiments were the base of the EUREKA 499 "Firetun" project). A total of 21 tests were performed using rail and metro vehicles, passenger cars, heavy goods vehicles, and calibrated fires (heptane pools and wood cribs). About 400 sensors were installed along the tunnel and inside the fire loads. The measurements dealt with air and wall temperature, velocity, opacity, gases concentration, smoke motion (video network), and so forth.

In these tests performed in Norway, special attention was paid to the smoke development and the smoke dispersal resulting from the combustion of vehicles (cars and trucks). The fire load was between 5,000 MJ (4.7 MBtu) for cars and 90,000 MJ (85.3 MBtu) for heavy goods vehicles.

One fire test was performed with n-heptane C7H16 (84% C and 16% H). The density of n-heptane is about 680 kg/m^3 (at 15°C) or 42.5 lb/ft^3 (at 59°F), the calorific value is approximately 44.4 MJ/kg (19,089 Btu/lb). Therefore, this fuel is very similar to gasoline or diesel oil. The mean value of the tunnel cross section was approximately 30 m^2 to 35 m^2 (323 to 377 ft^2). As compared to fire tests performed with gasoline, diesel oil, and n-heptane, special attention must be paid to two factors that heavily influence the smoke development and the dispersal of smoke in fires involving real road vehicles:

- The materials used for the vehicle construction (without load) are flame-retardant and hardly combustible.

- The natural initial temperatures at the tunnel wall in the test tunnel were relatively low. In addition, the tunnel wall was roughly excavated and very rough, so that the heat released was rapidly conveyed to the rock.

Both factors retard the heat release and thus the smoke development, and they reduce the fire temperatures compared to fuel fires. On the other hand, these fires last much longer than fuel fires. In addition, the smoke temperatures decreased rapidly with increasing distance from the fire site. This allowed the smoke to become more quickly cooled down and then sink to the ground. The total tunnel cross section was filled with smoke. In contrast to other fire tests, where there is normally a ground zone without smoke, at least for a period of time, there was no such free zone during these fires (except in the case of a wood fire). Therefore, the conditions in this test were significantly worse than in the case of fuel fires.

E-1.5 Memorial Tunnel Tests:

Memorial Tunnel (United States, 1993–1995) (*21, 25, 26*)

Description of Facility

- Length: 2,800 ft (853.4 m)
- Cross section: Former two-lane road alignment

This facility is an abandoned two-lane tunnel near Standard, West Virginia. The tunnel was converted to a fire ventilation laboratory in 1993 to study the behavior of smoke and heat under various ventilation systems (see Figure E1). Instrumentation includes temperature sensors, video cameras, and velocity probes. In contrast with the Zwenberg Tunnel and the Ofenegg Tunnel, the cross section in this tunnel was representative of usual road tunnels (approx. 60.5 m^2 or 651 ft^2 without intermediate ceiling). Diesel oil was used as a fire source. The density of diesel oil is between 815 kg/m^3 (50.9 lb/ft^3) and 855 kg/m^3 (53.4 lb/ft^3) at 15°C (59°F). The lower calorific value is 42.5 MJ/kg (18,284 Btu/lb). In terms of weight percentage, diesel oil mainly consists of carbon (86%) and hydrogen (14%). The stoichiometric air consumption is 14.5 kg (32 lb) of air per kilogram of diesel oil. Except for the fact that diesel oil ignition qualities are not as good as those of gasoline, there are no major differences between diesel oil and gasoline in terms of smoke development and in terms of smoke dispersal.

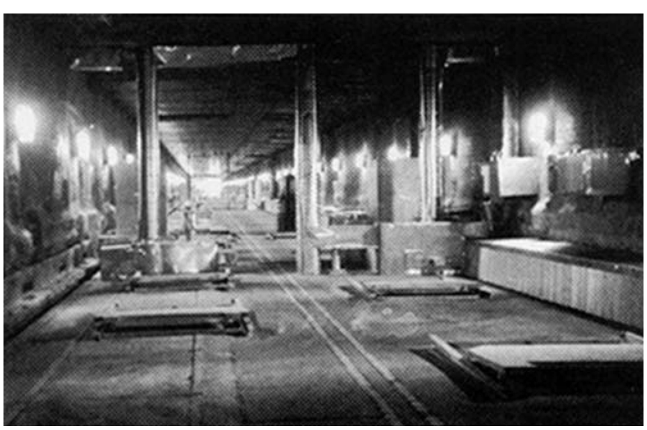

FIGURE E1 Measuring equipment in the Memorial Tunnel; velocity cabinet, data acquisition unit, and instrument tree (*26*).

E-1.6 Runehamar Tunnel Tests

Runehamar Tunnel Tests (*27*)

In total, four tests were performed using a simulated HGV. In three tests, mixtures of different cellulose and plastic materials were used. In one test, a "real" commodity, consisting of furniture and fixtures, was used. In all tests, the mass ratio was approximately 80% cellulose and 20% plastic. A polyester tarpaulin covered the cargo. The reason for using furniture in one of the tests was to provide a comparison to a past test (EUREKA 499), which was carried out with similar materials and a very high ventilation rate of 6 m/s (1,180 fpm) at the start of the test. This provided a good point of reference between the data from Runehamar and the EUREKA tests.

In the first two fire tests, Test 1 and Test 2, a pulsation of the fire was experienced during a time period when the fire was over 130 MW (444 MBtu/hr). This created a pulsating flow situation at the measuring station. The measurements showed that the maximum velocity was pulsating in the range of 3 to 4 m/s (591 to 787 fpm) down to a minimum in the range of 1 to 1.5 m/s (197 to 295 fpm). The frequency of the maximum velocities was about 45 seconds during this period. Since the air mass flow rate is dependent on the air velocity the HRR also pulsate during this period.

E-1.7 UPTUN Project Tunnel Tests (28)

This project was discussed earlier. The WP2 was devoted to the analysis of fire development in tunnels and potential mitigation measures. Design fire scenarios and associated design fire curves were proposed by UPTUN WP2, and used as input to other work packages within UPTUN. These design fires can also be used in more general terms since they are based on current knowledge about fire scenarios as well as information created within the UPTUN project. All of the large vehicles have been burned in a tunnel, whereas passenger cars have either been burned under a calorimeter or in a tunnel.

Small pool fires and small idle pallet fires, with a potential heat release rate of 10–20 MW (34–68 MBtu/hr), were also tested.

A characteristic of the UPTUN experiments is the use of real road and rail vehicles as fire loads. The heat release rate of such fires was one of the unanswered fundamental questions for fire life safety systems design.

This project was discussed earlier. The WP2 was devoted to the analysis of fire development in tunnels and potential mitigation measures. Design fire scenarios and associated design fire curves were proposed by UPTUN WP2, and used as input to other work packages within UPTUN. These design fires can also be used in more general terms since they are based on current knowledge about fire scenarios as well as information created within the UPTUN project. All of the large vehicles have been burned in a tunnel, whereas passenger cars have either been burned under a calorimeter or in a tunnel.

Small pool fires and small idle pallet fires, with a potential heat release rate of 10–20 MW (34–68 MBtu/hr), were also tested.

A characteristic of the UPTUN experiments is the use of real road and rail vehicles as fire loads. The heat release rate of such fires was one of the unanswered fundamental questions for fire life safety systems design.

APPENDIX F

Comparison of National and International Standards Requirements

F1 Tunnel Ventilation

This section provides comparison tables on tunnel ventilation requirements in different national and international standards. It covers Natural Ventilation (Table F1-1), Longitudinal Ventilation (Table F1-2), Transverse Ventilation (Table F1-3), and Emergency Exits Pressurization requirements (Table F1-4).

TABLE F1-1
NATURAL VENTILATION (NFPA 502*, 56, 77*)

Country/ Guideline	Requirement
France/ Circ2000-63A2	3.2.2 Arrangements for smoke ventilation will be required for tunnels in excess of the following lengths: 300 m (984.3 ft) in the case of urban tunnels, 500 m (1,640.4 ft) in the case of non-urban tunnels which are not for light traffic (…800 m or 2,624.7 ft provided that the absence of ventilation is compensated …), 1,000 m (3,280.8 ft) for light traffic tunnels.
Switzerland/ Design	Natural ventilation (piston effect) is sufficient for bidirectional traffic tunnels < 200 m (656.2 ft) - one directional traffic tunnels several hundred meters decision/calculation see guideline "Ventilation of Road Tunnels"
Switzerland/ Ventilation	Contains a decision system which of the three main categories—natural, mechanical without extraction, mechanical with extraction—becomes necessary. Decision criteria are: - traffic type and volume - tunnel length - tunnel gradient It also contains parameters and methods for a detailed calculation of the chosen system. The calculation systems for normal and emergency case operation are described, including fire loads.
Germany/ RABT	2.3.3.3 …. In short tunnels it is less reasonable to control the smoke with ventilators. For that reason tunnels shorter than 400 m (1,312.3 ft) resp. 600 m (1,968.5 ft) do not have fire ventilation…
Austria/RVS	RVS 9.261 Permitted if the fresh air demand during normal operation is ensured and the length of the escape routes is within the limits.
Norway	601 … For tunnels shorter than 250 m (820.2 ft) only safety equipment in terms of lighting is required. …
UK/BD78/99	5.13 In many short one-way tunnels, of up to 300 m (984.3 ft) length, the 'piston effect' of vehicle induced air flow will provide satisfactory natural ventilation for normal environmental needs, also emergency evacuation routes to places of refuge can be made acceptably short … 5.78 … Except for shorter tunnels …, a lack of positive control of smoke direction is not acceptable…
Japan	For tunnels over 1500 m for class AA tunnels, either ventilation system or parallel escape tube should be provided.
NFPA 502 (2008 edition)	10.1.1* Emergency ventilation shall not be required in tunnels exceeding 240 m (800 ft) in length, where it can be shown by an engineering analysis, using the design parameters for a particular tunnel (length, cross-section, grade, prevailing wind, traffic direction, 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 the authority having jurisdiction. I.1 Some short tunnels are ventilated naturally (without fans); however, such tunnels could necessitate a ventilation system to combat a fire emergency.

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TABLE F1-1
(*continued*)

Country/ Guideline	Requirement
Netherlands/NL-Safe	12.1 For tunnels shorter than 250 m (820.2 ft) mechanical ventilation is not required. Due to the short time for escape it is important that the possibilities and measures (for escape) are sufficient in relation to the choice of natural ventilation. Tunnel constructions of more than >250 m (820.2 ft) and less than <500 m (1,640.4 ft) offer the possibility to opt for natural ventilation or mechanic ventilation. Tunnels longer than 500 m (1,640.4 ft) always need a mechanic ventilation system. 12.2 For natural ventilation the closed structure must be short or techniques of horizontal slots in the roof or dampers must be applied.

TABLE F1-2
LONGITUDINAL VENTILATION (NFPA 502, *77*)

Country/ Guideline	Requirement
France/ Circ2000-63A2	3.2.2 … Longitudinal ventilation is possible for non-urban one-way tunnels: up to a length of 5000 m (16,404.2 ft); urban one-way tunnels up to 500 m (1,640.4 ft)…(for light traffic up to 800 m or 2,624.7 ft); non-urban two-way tunnels: up to 1000 m (3,280.8 ft) (for light traffic up to 1,500 m or 4,921.3 ft). Longitudinal ventilation is prohibited for urban two-way tunnels. The ventilation must be started up as soon as possible under conditions that will make it possible to achieve at least 3 m/s (591 fpm) in the direction of traffic movement. (For urban tunnels or two-way tunnels the ventilation control may be more delicate in order to maintain stratification).
Switzerland/ Ventilation	Two types are described: Longitudinal ventilation without extraction Longitudinal ventilation with extraction through a separate channel with steerable flaps Decision and calculation system, see guideline "Ventilation of Road Tunnels" Calculation data for jet fans are included Calculation data for extraction are included Calculation data for flaps are included
Germany/RABT	2.3.5.1.2 … In case of fire the longitudinal ventilation can … be activated to control the velocity of the smoke. 2.3.3.3 … For longer tunnels the smoke is discharged through openings in the ceiling at limited sections or blown in one direction from the site of the fire. Singular discharge can reduce the smoke spread for long tunnels. For longitudinal ventilation the traffic situation, the site of the fire, and the velocity of the tunnel air are decisive for the operation of the ventilation. For contraflow and congestion the use of longitudinal ventilation is only possible with limitations. For this reason a risk evaluation must be carried out for tunnel lengths over 600 m (1,968.5 ft)… 2.3.3.4 Critical air velocity 2.3 to 3.6 m/s (453 to 709 fpm) (indicated in a table depending on tunnel shape, gradient and fire output).
Austria/RVS	RVS 9.261 If natural ventilation does not ensure sufficient supply of fresh air or if the escape routes are above limits mechanical ventilation is necessary. Possible systems are longitudinal, semi transversal and transversal. For dimensioning of the system, normal operation phase and emergency (fire) operation phase must be taken into account. The three main aims are: - Enable self-rescue due to smoke prevention for a sufficient time and ventilation of escape tubes - Ensuring reasonable conditions for rescue staff - Reduction of damage to people, vehicles and tunnel structure A decision system based on risk factors, a catalogue of measures and special demands for each ventilation system are given.

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TABLE F1-2
(*continued*)

Country/ Guideline	Requirement
Norway/Road Tunnels	1004.21 Mechanical longitudinal ventilation is … based on the use of impulse fans. In long tunnels with heavy traffic, or where there are particular restrictions…, the use of ventilator shaft may be considered. 1005 … the ventilation system shall also be designed to control a fire of 5 MW (17 MBtu/hr) or 20 MW (68 MBtu/hr) depending on the traffic volume…For tunnels with gradient <2% the net design air velocity shall be a minimum 2 m/s (394 fpm) for tunnels designed for car fires (5 MW or 17 MBtu/hr) and minimum 3.5 m/s (689 fpm) for HGV fires (20 MW or 68 MBtu/hr)…
UK/BD78/99	For tunnels of between 300 to 400 m (984.3 to 1,312.3 ft) in length, mechanical ventilation plant will need to be considered with respect to fire smoke control, for example, where traffic is relatively light and/or gradients are not steep, the length of tunnel where mechanical ventilation plant is unlikely to be required may be increased to 400 m (1,312.3 ft). Mechanical ventilation is required for all longer (400 m or 1,312.3 ft and over) tunnels and for (200 m or 656 ft and over) tunnels on steep gradients or those subject to frequent congestion, either due to high usage or external traffic conditions… 5.16 Longitudinal ventilation is the simplest form of tunnel ventilation and because of lower capital and running cost benefits is often the first choice. … 5.91 Fans for tunnel air control shall be reversible … 5.22 Calculations of jet fan capacity shall take into account that air velocities shall be sufficient for control of fire smoke. The fans shall be capable of reverse operation … 5.74 The initial velocity of smoke layer advance is about 1.3 m/s (256 fpm) for a 3 MW (10 MBtu/hr) car fire and 3.0 m/s (591 fpm) for a 25 MW (85 MBtu/hr) truck fire, depending on the tunnel geometry. A gasoline tanker fire of 50 to 100 MW (171 to 341 MBtu/hr) could generate a smoke velocity of 7.0 m/s (1,378 fpm) or more, which requires large and high cost ventilation plant provisions to be able to cope successfully. Ventilation normal provision for tunnel class AA, A, B, to be considered for C, D.
Netherlands/NL-Safe	12.1 Tunnels over 500 m (1,640.4 ft) always need a mechanical ventilation system… Longitudinal ventilation is suitable for tunnels over 250 m (820.2 ft). 12.2 Longitudinal ventilation is applied only in tubes with one-directional traffic. The ventilation design has to take into account: the fire intensity, the location of the fire …, influence of the wind, the resistance in ventilation by the vehicles, influence of the longitudinal slope on the draught.
NFPA 502 (2008 edition)	10.2.4 In tunnels with unidirectional 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 greater than the 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 away from the site first. 10.4 Design Objectives. The design objectives of the emergency ventilation system shall be to control, to extract, or to control and extract, smoke and heated gases as follows: (2) Longitudinal airflow rates are produced to prevent backlayering of smoke in a path of egress away from a fire (Annex D provides methodology for Critical Velocity Calculations).
EU/2004/54/EC	2.9.2 A mechanical ventilation system shall be installed in all tunnels longer than 1000 m (3,280.8 ft) with traffic volume higher than 2,000 vehicles per lane. 2.9.3 In tunnels with bidirectional and/or congested unidirectional traffic, longitudinal ventilation shall be allowed only if a risk analysis according to Article 13 shows it is acceptable and/or specific measures are taken, such as appropriate traffic management, shorter emergency exit distances, smoke exhausts at intervals.

TABLE F1-3
TRANSVERSE VENTILATION (*20, 66*)

Country/ Guideline	Requirement
France/ Circ2000-63A2	3.2.2 …the objectives for transverse ventilation systems are to… retain a layer of pure air close to the roadway, and to extract smoke … at roof level. Smoke extraction…must be capable of being achieved over a distance of the order of 400 m (1,312 ft) in an urban tunnel and 600 m (1,968 ft) in a non-urban tunnel…. If fresh air blower blocks are more than 800 m (2,625 ft) long, provision must be made for the possibility of blowing fresh air into the lower part of the tunnel under all circumstances. This imposes a requirement for blower outlets at the base of the side walls and means for delivering fresh air to the duct feeding them at all times… The start-up of smoke extraction requires a human presence at all times, or an automatic system, which includes fire detection. When the tunnel has a human presence offering rapid and accurate control at all times it is most effective that smoke is extracted using smoke vents in the roof which are opened under remote control. Vents are placed per 50 m or 164 ft (not more than 100 m or 328 ft apart in non-urban tunnels).
Switzerland/ Ventilation	Transversal ventilation with one fresh air channel and one extraction channel with adjustable flaps.
Germany/RABT	2.3.5.3 Today the only economical use of transverse ventilation is in cases of long tunnels… 2.3.5.2 Semi-transverse ventilation… the inlets are placed at the road level in regular distances ≤20 m 65.6 ft. Normally, the inflow velocity can be up to 10 m/s (2,000 fpm). However, it is not to exceed 3 m/s (591 fpm) when there is a fire. The polluted air is usually discharged through the portals… For long tunnels semi-transverse ventilation in sections (point extraction) can be an economical alternative to longitudinal ventilation…
UK/BD78/99	5.30 Fully transverse ventilation is the most comprehensive form of mechanical ventilation, but because of its high capital and operational costs, is seldom adopted for new tunnels. 5.37 Semi transverse ventilation has frequently been used in UK tunnels at river crossings. Ventilation normal provision for tunnel class AA, A, B, to be considered for C, D.
Netherlands/NL-Safe	12.1 When … traffic intensities and tunnel length increases, also the risk of congestion increases in case of a (fire) accident. Transversal ventilation can become an alternative for this. Though warning is given to this transversal ventilation for its limited capacity of removing smoke and for its reliability. A better option would be the creation of open spaces in the tunnel (cutting the tunnel into several smaller parts).
NFPA 502 (2008 edition)	10.2.4 In tunnels with unidirectional traffic where motorists are likely to be located upstream of the fire site, the following objectives shall be met: (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. 10.4 Design Objectives. The design objectives of the emergency ventilation system shall be to control, to extract, or to control and extract, smoke and heated gases as follows: (1) A stream of noncontaminated air is provided to motorists in a path of egress away from a fire.
EU/2004/54/EC	2.9.2 A mechanical ventilation system shall be installed in all tunnels longer than 1000 m (3,280 ft) with a traffic volume higher than 2,000 vehicles per lane. 2.9.4 Transverse or semi-transverse ventilation systems shall be used in tunnels where a mechanical ventilation system is necessary and longitudinal ventilation is not allowed according to 2.9.3. These systems shall be able to exhaust smoke in case of fire.

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TABLE F1-3
(*continued*)

Country/ Guideline	Requirement
	2.9.5 For tunnels with bi-directional traffic, with a traffic volume higher than 2,000 vehicles per lane, longer than 3000 m (9,842 ft) and with a control centre and transverse and/or semi-transverse ventilation, the following minimum measures shall be taken as regards 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.

TABLE F1-4
EMERGENCY EXITS PRESSURIZATION (NFPA 502, *77*)

Country/ Guideline	Requirement
France/Circ2000-63A2	3.2.3 a) Communications between tubes: The airlocks provided in the communication facilities between tubes must be provided with a ventilation system providing them with an excess pressure of approximately 80 Pa (0.0116 psi) with respect to the tube in which an incident or accident has occurred. b) Safety tunnel parallel to the tunnel: Whenever in use the tunnel is to be ventilated and the communication airlocks (or the tunnel itself in the absence of airlocks) is to have an excess pressure of approximately 80 Pa in comparison with the tunnel. c) Shelters: Shelters are to be equipped with a specific ventilation system. Air quality is to be maintained at all times by renewing the volume in the shelter three times per hour.
Switzerland/ Ventilation	Separate guideline “Ventilation of Safety- and Cross-passages in Road Tunnels.”
Germany/RABT	2.5.1.3 The escape routes must be kept free of smoke. For this purpose locks or overpressure are useful measures.
UK/BD78/99	3.17 Cross passages and escape shafts … require ventilation to maintain a supply of fresh air to the escape route and positive pressure or other provisions to exclude smoke from any fire within a traffic bore. Where two or more bores are linked by cross connections, the effect of opening one or more of those cross connection doors shall be considered.
NFPA 502 (2008 edition)	7.14.1.1* The means of egress requirements for all road tunnels and those roadways beneath air-right structures that the authority having jurisdiction determines are similar to a road tunnel shall be in accordance with NFPA 101, Chapter 7, except as modified by this standard. 7.14.2 Tenable Environment. A tenable environment shall be provided in the means of egress during the evacuation phase. 7.14.5.5 The force required to open the doors fully when applied to the latch side shall be as low as possible, but shall not exceed 222 N (50 lb).
Netherlands/NL-Safe	11.4 ... Escape tubes… must be safe …control of a smokeless situation in escape routes.

F2 Tunnel Ventilation

Appendix F2 provides comparison tables on tunnel fire protection requirements in different national (including NFPA 502, 2008 edition) and international standards. It covers the fire fighting equipment (extinguisher, hose-reels, and so forth) and water requirements.

TABLE F2-1
FIRE FIGHTING (PORTABLE EXTINGUISHER, HOSE-REELS, AND SO FORTH) AND WATER REQUIREMENTS (NFPA 502, *56, 77*)

Country/ Guideline	Requirement
France/Circ2000-63A2	3.5.1 Two standard portable extinguishers having a recommended unit capacity of 6 kg (13.2 lb)… are to be located in the emergency recesses … It is recommended that water with additive extinguishers should be used. 2.5 Fire-fighting equipment …must preferably be located in recesses, which are separate from emergency recesses. 3.5.2 The provision of a water supply is not compulsory in non-urban tunnels less than 500 m (1,640 ft) long. In other circumstances, unless different arrangements are agreed by local authorities, a water pipe is to be installed. Fire-fighting equipment of the riser or hydrant type delivering 120 m^3 (4,238 ft^3) at a pressure of 0.6 MPa (87 psi) are to be installed approximately every 200 m (656 ft). In the case of a tunnel in which there is a change in level, a range of 0.4 to 0.8 MPa (58 to 116 psi) shall be accepted. The delivered flow from a hydrant must be 60 m^3/h (264 gpm).
Switzerland/ Design	Two 6 kg (13.2 lb) fire extinguishers placed at each emergency telephone station, in bidirectional traffic tunnels every 150 m (492 ft), alternating on each side, in one directional traffic tunnels every 300 m (985 ft) on the outer side. Connection to the control room which indicates if a fire extinguisher is taken. Hydrants and pipes are not prescribed, but if they are installed the following parameters must be met: 20 L/sec (317 gpm), hydrants every 150 m (492 ft), reservoir 250 m^3 (8,830 ft^3).
Germany/RABT	2.5.4.1 (For tunnels > 400 m or 1,312 ft) Two 6 kg (13.2 lb) (net) handheld extinguishers are placed at each emergency point (distance < 150 m or 492 ft). 2.5.4.2 Tunnels with length ≥ 600 m (1,968 ft) (400 m (1,312 ft) at high HGV traffic > 4,000 HGV × km/tube/day) must be equipped with fire hydrant… the pipes shall be designed for 1200 L/min (317 gpm) at 6 to 10 bar (87 to 145 psi). The connectors are placed opposite the emergency points at distances less than 150 m (492 ft). For tunnels < 400 m (1,312 ft) fire hydrant shall be available at the portals.
Austria/RVS	RVS 9.233 Dimension of fire fighting equipment recess. RVS 9.281 Fire fighting equipment recesses are necessary in tunnels over 500 m. They have to be positioned just opposite the emergency telephone stations and half way between the emergency telephone stations. Thus they are on both sides with a = 250 m (820 ft). RVS 9.282 At each fire fighting equipment recess and at each emergency telephone station two extinguishers (6 L and 9 L) must be available. RVS 9.281 Water reservoir of 80 m^3 (2,825.2 ft^3), refilled in 24 h. RVS 9.282 Hydrants at each fire fighting equipment recess and at the portals fed through water main [dry pipe only for tunnels 500 to 1000 m (1,640 to 3,280 ft). Necessary for category III and IV, recommended for all categories. Capacity 20 L/sec (317 gpm) for 1 h.
Norway/Road Tunnels	602.205 Fire extinguishers should be at least 6 kg (13.2 lb) ABC and must be located in separate compartments. 602.1 Class B every 250 m (820 ft), C, D every 125 m (410 ft), E every 125 m (410 ft), F every 62.5 m (205 ft). 602.206 Possible solutions are: separate reservoirs (approximately 6 m^3) in connection with the drainage system, a water tanker vehicle with sufficient capacity (approximately 6 m^3 or 212 ft^3) firewater reservoir at the low point of the tunnel. In special cases where pressurized water is easily available (e.g., in a tunnel located in a town) a continuous water main can be an alternative.

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TABLE F2-1
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Country/ Guideline	Requirement
UK/BD78/99	3.26 …Facilities for …responding to a fire shall be provided to safeguard all areas of the tunnel including the tunnel services building. 3.12 Emergency Points … shall be large enough to house fire-fighting facilities and emergency roadside telephones connected to… control centres.... The nominal spacing for emergency points is 50 m (164 ft), with emergency roadside telephones and fire hose reels… at 100 m (328 ft) intervals. Hand held fire extinguishers are normally provided in tunnel class AA, A, B. To be considered in class C. Pressurized Fire Hydrants normally provided in tunnel class AA, A, B, C, to be considered in class D.
Germany/RABT	2.5.4.1 (For tunnels > 400 m or 1,312 ft) Two 6 kg (13.2 lb) (net) handheld extinguishers are placed at each emergency point (distance < 150 m or 492 ft). 2.5.4.2 Tunnels with length ≥ 600 m (1,968 ft) (400 m (1,312 ft) at high HGV traffic > 4,000 HGV × km/tube/day) must be equipped with fire hydrant… the pipes shall be designed for 1200 L/min (317 gpm) at 6 to 10 bar (87 to 145 psi). The connectors are placed opposite the emergency points at distances less than 150 m (492 ft). For tunnels < 400 m (1,312 ft) fire hydrant shall be available at the portals.
Austria/RVS	RVS 9.233 Dimension of fire fighting equipment recess. RVS 9.281 Fire fighting equipment recesses are necessary in tunnels over 500 m. They have to be positioned just opposite the emergency telephone stations and half way between the emergency telephone stations. Thus they are on both sides with a = 250 m (820 ft). RVS 9.282 At each fire fighting equipment recess and at each emergency telephone station two extinguishers (6 L and 9 L) must be available. RVS 9.281 Water reservoir of 80 m^3 (2,825.2 ft^3), refilled in 24 h. RVS 9.282 Hydrants at each fire fighting equipment recess and at the portals fed through water main [dry pipe only for tunnels 500 to 1000 m (1,640 to 3,280 ft)]. Necessary for category III and IV, recommended for all categories. Capacity 20 L/sec (317 gpm) for 1 h.
Norway/Road Tunnels	602.205 Fire extinguishers should be at least 6 kg (13.2 lb) ABC and must be located in separate compartments. 602.1 Class B every 250 m (820 ft), C, D every 125 m (410 ft), E every 125 m (410 ft), F every 62.5 m (205 ft). 602.206 Possible solutions are: separate reservoirs (approximately 6 m^3) in connection with the drainage system, a water tanker vehicle with sufficient capacity (approximately 6 m^3 or 212 ft^3) firewater reservoir at the low point of the tunnel. In special cases where pressurized water is easily available (e.g., in a tunnel located in a town) a continuous water main can be an alternative.
UK/BD78/99	3.26 …Facilities for …responding to a fire shall be provided to safeguard all areas of the tunnel including the tunnel services building. 3.12 Emergency Points … shall be large enough to house fire-fighting facilities and emergency roadside telephones connected to… control centres.... The nominal spacing for emergency points is 50 m (164 ft), with emergency roadside telephones and fire hose reels… at 100 m (328 ft) intervals. Hand held fire extinguishers are normally provided in tunnel class AA, A, B. To be considered in class C. Pressurized Fire Hydrants normally provided in tunnel class AA, A, B, C, to be considered in class D. Fire Hose Reels normally provided in tunnel class AA, to be considered in class A, B, C. 8.55 Automatic fire extinguishing systems are not considered suitable for the traffic space. Total flood gaseous systems and foam systems are not practical where people are present in vehicles. Water sprinkler systems may cool buoyant smoke causing immediate smoke logging of the tunnel and producing potentially explosive air/vapor mixes.

TABLE F2-1
(*continued*)

Country/ Guideline	Requirement
Netherlands/NL-Safe	15.1 nr. 2. For a tunnel there is no need for provisions of fire suppression by tunnel users, except if the economic value of the tunnel asks for this. Then fire extinguishers are recommended under the condition that there is monitoring. 15.2 nr. 5 In tunnels of large economic value and with a mechanical. ventilation system, hose-reels are recommended. The distance between the hose-reels must be limited to 60 m (197 ft). 15.2 nr. 6 In first aid stations with hose-reels a fire extinguisher shall also be provided. 15.3 nr. 12A system of fire fighting consists of a distribution system (hose-reels), and possibly completed with a system to increase the water pressure and a system of water feeding. 15.3 nr. 13 If the tunnel has a large economical value consideration has to be made for the construction of a permanent installation for the increase of water pressure and a water reservoir. 15.2 nr. 7 A foaming substance shall be added to the extinguishing medium. 8.3 nr. 6c Fixed fire suppression mitigation systems as sprinklers can be used for mitigating the heating of the concrete and the reinforcement in the Netherlands sprinkler system is not yet applied because of disadvantages, though it will be applied in the tunnel of the 'Betuwelijn.'
Sweden	In tunnels > 500 m there should be extinguishers at each portal and at least every 150 m. The extinguisher should meet SS-EN 3-7 requirements. They should contain 6 kg ABC powder and manage the test fires 34A and 183B. Hose connections required at each portal and at least every 150 m.
PIARC	The minimum content of 6 kg when the traffic includes mainly passenger cars. The maximum of 9 kg when heavy goods vehicles are numerous. Extinguisher removal alarms recommended. For tunnels from 200 to 1000 m long (case based), water supply requirement is 1000 L/min, 0.5 MPa (standpipe). Hydrants 100–2000 m spacing.
UNECE	Fire extinguishers should be installed systematically in tunnels and in their entrances. Water supply shall be available for fire brigade.
Australia	Dry chemical extinguisher (equipment niche, 60 m spacing) and CO_2 extinguishers adjacent to all electrical switchboards, control panels. Hydrants at 60 m spacing (hose reels). Hydrants with fittings located in each cabinet.
Japan	For tunnels Class D (>100 m) two 6 kg extinguishers at 50 m spacing required. For tunnels Class A or Class B (>1000 m) water supply requirement is 130 L/min, 0.17 MPa (1.7 kgf/cm^2). Hydrants < 50 m spacing.
Korea	Two 3.3 kg (>3 Unit Capacity) extinguishers. <50 m spacing. Extinguisher removal alarms recorded. NFSC: For tunnels over 1000 m long water supply requirement is 130 L/min, 0.17 MPa (1.7 kgf/cm^2). Hydrants < 50 m spacing. Minimum water discharge time: 20 min. GIST: For tunnels over 1000 m long water supply requirement is 190 L/min, 0.3 MPa (3 kgf/cm^2) Hydrants < 50 m spacing. Minimum water discharge time: 40 min hose connections less than 50 m for tunnels class 2 or higher over 1000 m long.

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TABLE F2-1
(*continued*)

Country/ Guideline	Requirement
NFPA 502 (2008 edition)	7.8.1 Portable fire extinguishers, with a rating of 2-A:20-B:C, shall be located along the roadway in approved wall cabinets at intervals of not more than 90 m (300 ft). 7.8.2 To facilitate safe use by motorists, the maximum weight of each extinguisher shall be 9 kg (20 lb). 7.8.3 Portable fire extinguishers shall be selected, installed, inspected, and maintained in accordance with NFPA 10. Annex J. Fire Apparatus. J.3 Extinguishers. Fire-fighting units should carry multipurpose, dry chemical extinguishers and an extinguishing agent for Class D metal fires. 7.7 Standpipe, Fire Hydrants, and Water Supply. Standpipe, fire hydrants, and water supply systems in road tunnels shall be provided in accordance with the requirements of Chapter 9. 9.2.1 Wet standpipe systems (automatic or semiautomatic) shall be connected to an approved water supply that is capable of supplying the system demand for a minimum of 1 h. 9.2.2 Dry standpipe systems shall have an approved water supply that is capable of supplying the system demand for a minimum of 1 h. 9.4.1 Hose connections shall be spaced so that no location on the protected roadway is more than 45 m (150 ft) from the hose connection. 9.4.2 Hose connection spacing shall not exceed 85 m (275 ft). A.5.3 Where a municipal or privately owned waterworks system is available, consideration should be given to providing fire hydrants along limited access highways at spacing not to exceed 305 m (1,000 ft). The minimum required water supply for fire hydrants should not be less than 3,780 L/min (1,000 gpm) at 1.4 bar (20 psi) from each of two hydrants flowing simultaneously.
EU/2004/54/EC	2.10.1 Emergency stations are intended to provide various items of safety equipment, in particular emergency telephones and extinguishers, but are not intended to protect road users from the effects of fire. 2.10.2 Emergency stations can consist of a box on the sidewall or preferably a recess in the sidewall. They shall be equipped with at least an emergency telephone and two fire extinguishers. 2.10.3 Emergency stations shall be provided near the portals and inside at intervals which for new tunnels shall not exceed 150 m (492 ft) and which in existing tunnels shall not exceed 250 m (820 ft). 2.11 Water supply. A water supply shall be provided for all tunnels. Hydrants shall be provided near the portals and inside at intervals which shall not exceed 250 m (820 ft). If a water supply is not available, it is mandatory to verify that sufficient water is provided otherwise.

F3 Tunnel Fire Detection

Appendix F3 provides comparison tables on tunnel fire smoke detection requirements in different national (including NFPA 502, 2008 edition) and international standards.

TABLE F3
FIRE/SMOKE DETECTION (VENTILATION SENSORS OR SPECIFIC FIRE DETECTION)
(NFPA 502, *56, 77*)

Country/ Guideline	Requirement
France/ Circ2000-63A2	3.6 In tunnels where there is no permanent human supervision … an automatic fire detection system is required, whenever the ventilation system, which is used in the event of a fire, is not that which is automatically brought into use in the event of serious tunnel pollution… in other cases to be considered.
Switzerland/ Design	Automatic fire detection system which reacts to the degree of temperature as well as to temperature progress, able to detect a 100 L fuel fire. Connected to the control room and to the traffic signals, switching them on red in driving direction towards the fire.
Switzerland/ Ventilation	If mechanical ventilation is applied an automatic smoke detection system is obligatory. Distance between measurement point <300 m (984 ft) (see separate Guidelines Fire Detection).
Germany/RABT	2.3.6 … Ventilation sensors… 2.5.3.2 Automatic fire alarm equipment must be installed for tunnel length over 400 m (1,312 ft) and for tunnels with mechanical ventilation. 2.3.6… As guidance for the sensitivity of the fire detection: a fire of 5 MW (17 MBtu/hr) shall be observed within half a minute at up to 6 m/s (1,181 fpm) air velocity. The fire shall be localized with an accuracy of 50 m (164 ft).
Austria/RVS	RVS 9.282 Automatic fire detectors in operation rooms and lay by. Generally in the tunnel if there is a mechanical ventilation system.
UK/BD78/99	Fire detection mentioned for sumps and service buildings only. Smoke detection.
Netherlands/NL-Safe	14.2 nr. 4 Apply a measurement of visibility for smoke detection... 14.2 nr. 2 In tunnels with an automatic ventilation system; apply a measurement of visibility to determine the concentration of NO_2. When the concentration is too high, the system has to activate the automatic ventilation system. 14.2 nr. 6 Consider the application of measurement of temperature to detect fire. 14.2 nr. 7 Consider the application of a detection system to detect high risk explosive gases.
Korea	GIST: Manual pull stations (push button) shall be installed around the hydrant cabinets or inside fire extinguisher cabinets spaced less than 50 m in tunnels over 500 m long. An automatic fire detection system is required in tunnels over 500 m long or Class 3 and higher in bi-directional tunnels and in urban tunnels, or in all other tunnels over 1000 m long or Class 2. In tunnels over 2000 m, installation of monitoring system equipped with CCTV should be considered for detection of smoke and flame from fires. In tunnels between 500 m and 1000 m automatic fire detection system can be replaced by the automatic incident detection system.
Japan	Manual pull stations (push button) recommended to be installed with emergency telephones spaced less than 50 m in tunnels longer than Class C. An automatic fire detection system applied in tunnels longer than 300 m if the traffic flow is high and tunnels equipped with ventilation system (Class A and higher).

(*continued on next page*)

TABLE F3
(*continued*)

Country/ Guideline	Requirement
Sweden	Alarm push buttons or emergency telephones should be coordinated with the escape routes. Should be installed on both sides of the tunnel tube if three lanes or more. Spacing shall be less than 150 m apart for all classes of tunnels. An automatic fire detection system is required in tunnels class TB and higher.
NFPA 502 (2008 edition)	7.4.1 At least two systems to detect, identify, or locate a fire in a tunnel shall be provided, including one manual, means meeting the requirements of 7.4.1.2 and either a closed-circuit television (CCTV) system in accordance with 7.4.1.3 or an automatic fire detection system in accordance with 7.4.1.4. 7.4.1.2.1 Manual fire alarm boxes mounted in NEMA Enclosure Type 4 (IP 65) or equivalent boxes shall be installed at intervals of not more than 90 m (300 ft) and at all cross-passages and means of egress from the tunnel. 7.4.1.2.5 The system shall be installed, inspected, and maintained in compliance with NFPA 72. 7.4.1.3.1 CCTVs with or without traffic-flow indication devices shall be permitted to identify fires in tunnels with 24-hour supervision. 7.4.1.4 Automatic Fire Detection Systems. 7.4.1.4.1 Automatic fire detection systems installed in accordance with the requirements of NFPA 72 shall be installed in tunnels where 24-hour supervision is not provided. 7.4.1.4.3 Where a fire detection system is installed in accordance with the requirements of 7.4.1.4.1, the system shall be for fire detection only. 7.4.1.4.4 Automatic fire detection systems shall be capable of identifying the location of the fire within 15 m (50 ft). 7.4.1.4.5 Spot detectors shall have a light that remains on until the device is reset. 7.4.1.4.6 CCTV systems used for automatic fire detection shall be permitted when listed for the intended purpose and installed in accordance with the manufacturers' requirements and NFPA 72. 7.4.1.4.7 Automatic fire detection systems within a tunnel shall be zoned to correspond with the tunnel ventilation zones where tunnel ventilation is provided.
PIARC	Push button alarms are optional. An automatic fire detection system can be useful in tunnels that are long or complicated, especially when dangerous goods are allowed or when it is necessary to precisely determine the fire location. They can be also helpful in unmanned tunnels with transverse or semi-transverse ventilation.
EU/2004/54/EC	2.14.2 Automatic fire detection systems shall be installed in all tunnels, which do not have a control centre, where the operation of mechanical ventilation for smoke control is different from the automatic operation of ventilation for the control of pollutants.

F4 Tunnel Egress

Appendix F4 provides comparison tables on tunnel egress requirements in different national and international standards. It covers Parallel Escape Tube (Table F4-1), Emergency Cross Passages (Table F4-2), Shelters (Table F4-3), and Direct Pedestrian Emergency Exits (Table F4-4).

TABLE F4-1
PARALLEL ESCAPE TUBE (NFPA 502, *56*)

Country/ Guideline	Requirement
France/Circ2000-63A2	2.2.2 … A safety tunnel parallel to the tunnel is only to be constructed if this is justified for technical reasons (e.g., pilot tunnel)…
Germany/RABT	2.5.1.3 Escape doors can lead to a rescue tunnel, which can be used by pedestrians. The tunnel can be parallel to traffic tunnel and various emergency exits from the tunnel can be connected to a common exit to the opening. The longitudinal slope shall not be more than 10%; the cross section shall be 2.25 m × 2.25 m (7.4 ft x 7.4 ft).
Austria/RVS	The general safety concept shows two possibilities. - Limitation of escape routes (according to tunnel cross section) in combination with natural or longitudinal ventilation. - Transversal or semi-transversal ventilation with no limitation of escape routes. RVS 9.232 Dimension of escape routes 1.20 m x 2.20 m (3.9 ft x 7.2 ft), doors 1.0 m x 2.0 m (3.3 ft x 6.6 ft). RVS 9.281 Escape tubes for foot passengers or vehicles could be used to minimize the escape routes (see above). Dimensions are given.
UK/BD78/99	2.38 …A separate service tunnel…should be considered on a whole life cost basis…Such tunnels may also be used for evacuation purposes during an emergency.
Netherlands/NL-Safe	11.4 …Escape tubes must have a minimal width of 1.20 m (3.9 ft). Narrowing obstacles in escape tubes must be avoided as much as possible; the width here must still be 0.85 m (2.8 ft) minimal ….The escape route must be safe (no possible exits in smoking zones, no crossing of lanes with traffic) …Avoiding danger of stumbling (no steps).
Korea	Required for tunnels over 3000 m with bi-directional traffic or risky uni-directional tunnels. Can be installed in tunnels over 1000 m long with bi-directional traffic or urban tunnels with expected congestion.
Australia	A separate egress tunnel should be provided in tunnels, particularly with bi-directional traffic, or in tunnels in which adjacent tunnel cannot be used for escape purposes. For unidirectional tunnels, escape to adjoining road tunnel can be considered; however traffic management of the adjoining tunnel is required
Japan	Required for tunnels class AA, and for tunnels class A >3000 m long with bi-directional traffic and longitudinal ventilation system.
PIARC	Escape corridor or escape gallery can be one of evacuation possibilities.
NFPA 502 (2008)	Not required
EU/2004/54/EC	2.3.3 … Examples of such emergency exits are… exits to an emergency gallery ….

TABLE F4-2
EMERGENCY CROSS PASSAGE (NFPA 502, *56, 77*)

Country / Guideline	Requirement
France/ Circ2000-63A2	2.2 Arrangements for the evacuation and protection of users and emergency access … shall be provided on a systematic basis and access shall be provided approximately every 200 m (656 ft); a shorter spacing is to be used in tubes which are frequently congested and which have more than three lanes. In non-urban tunnels these arrangements are to be provided where lengths exceed 500 m (1,640 ft) and the spacing will be approximately 400 m (1,312 ft). 2.2.2 Communication between the (two) tubes represents a satisfactory arrangement … provided that a single door does not provide access from the tube in which the incident or accident occurred and a traffic lane in the other tube.
Switzerland/ Design	In two tube tunnels cross passages for pedestrians every 300 m (984 ft), for vehicles every 900 m (2,953 ft). In tunnels with high frequency of dangerous goods vehicles the following have to be applied: Cross passages have to be equipped in order to stop fire spread to the other tube. Emergency exits to a lower level have to be equipped with a ramp instead of stairways.
Switzerland/ Ventilation	Cross passages with length > 5 m (16.4 ft) need two doors.
Germany/ RABT	2.5.1.3 Escape routes must be indicated and illuminated. Tunnels ≥ 400 m (1,312 ft) must have emergency exits at regular distances ≤ 300 m (984 ft). The emergency exits can connect to the other tunnel tube directly or through a cross passage. Cross passages have doors in both ends.
Austria/RVS	RVS 9.233 Dimension and design of cross passages. RVS 9.281 Opposite each lay by (see S23) a cross passage for vehicles is situated (a = 1000 m or 3,280 ft). Additionally in tunnels without fire ventilation and in tunnels with a longitudinal gradient >3% a foot passenger cross passage is situated at each emergency call station (a = 250 m or 820 ft).
Norway/Road Tunnels	409 Cross passages. In tunnels with two parallel tubes pedestrian cross passages between the tubes shall be arranged for escape. These shall be located for every 250 m (820 ft)... 602.1 Pedestrian cross passages are required for tunnel class E and F.
UK/BD78/99	*3.16 Escape Routes:* In twin bore tunnels, passenger escape routes through fire doors positioned in central walls or cross-connecting passages, shall be provided. These shall be positioned at 100 m (328 ft) nominal intervals… 5.13 (100 m or 328 ft preferred limit, 150 m or 492 ft maximum limit). 3.17 *Tunnel Cross Connections*: Tunnel cross connections are generally of three types: i. A single set of fire doors in the partition wall between two traffic bores, ii. A cross passage with fire doors at both ends providing a safe refuge and an escape route from one bore to the other, iii. Normal provision for class AA, to be considered in class A and B.
Netherlands/ NL-Safe	11.4 Exit-doors for escape are necessary when the distance to open area is too long. Distance between those exit doors must be determined by quantitative risk analysis.
Korea	GIST: For tunnels over 500 m long or bi-directional tunnels with a parallel escape tube spacing between cross passages shall not exceed 250 m. For tunnels less than 1200 m long, spacing can be less than 300 m.

TABLE F4-2
(*continued*)

Country / Guideline	Requirement
Japan	For uni-directional tunnels over 750 m long spacing shall not exceed 750 m; for bi-directional tunnels over 400 m long spacing shall not exceed 350 m. The actual installation distance is 200–300 m
Sweden	For all tunnels spacing shall not exceed 150 m. The time for escape to portal, escape route, or other safe haven must not be longer than the tunnel can evacuate before the conditions become critical. The gradient of an escape route cannot be higher than 8%. Class TA should have increased fire protection; e.g., shorter distance between escape routes.
PIARC	The most common escape route in two tube tunnels is a connection (cross passage) between the two tubes. The distance between connections should depend on traffic density and emergency rescue scenarios; for instance 100–200 m in cities.
NFPA 502 (2008)	7.14.7.1 Where tunnels are divided by a minimum of 2-hour fire-rated construction or where tunnels are in twin bores, cross passageways between the tunnels shall be permitted to be utilized in lieu of emergency exits. 7.14.7.2 The following requirements shall be met: (1) Cross passageways shall not be farther than 200 m (656 ft) apart. (2) An emergency egress walkway with a minimum clear width of 1.12 m (3.6 ft) shall be provided on each side of the cross passageways. (a) Walkways shall be protected from oncoming traffic by either a curb, a change in elevation, or a barrier. (b) Walkways shall be continuous the entire length of the tunnel, terminating at surface grade. (c) Raised walkways in tunnels shall have guards in accordance with NFPA 101. (d) Intermediate rails shall not be required for walkway guards. (3) Where portals of the tunnel are below surface grade, surface grade shall be made accessible by a stair, vehicle ramp, or pedestrian ramp.
EU/2004/54/EC	2.3.3. Emergency exits allow tunnel users to leave the tunnel without their vehicles and reach a safe place in the event of an accident or a fire and also provide access on foot to the tunnel for emergency services. Examples of such emergency exits are: direct exits from the tunnel to the outside, cross connections between tunnel tubes, exits to an emergency gallery, shelters with an escape route separate from the tunnel tube. 2.3.4. Shelters without an exit leading to escape routes to the opening shall not be built. 2.3.5. Emergency exits shall be provided if an analysis of relevant risks, including how far and how quickly smoke travels under local conditions, shows that the ventilation and other safety provisions are insufficient to ensure the safety of road users. 2.3.6. In any event, in new tunnels, emergency exits shall be provided where the traffic volume is higher than 2,000 vehicles per lane. 2.3.7. In existing tunnels longer than 1000 m (3,280 ft), with a traffic volume higher than 2,000 vehicles per lane, the feasibility and effectiveness of the implementation of new emergency exits shall be evaluated. 2.3.8. Where emergency exits are provided, the distance between two emergency exits shall not exceed 500 m (1,640 ft). 2.3.9. Appropriate means, such as doors, shall be used to prevent smoke and heat from reaching the escape routes behind the emergency exit, so that the tunnel users can safely reach the outside and the emergency services can have access to the tunnel.

TABLE F4-3
SHELTERS (NFPA 502)

Country/ Guideline	Requirement
France/ Circ2000-63A2	2.2.2…Whenever none of the preceding arrangements apply, shelters are to be built to offer users a safe place while they await evacuation. Each shelter shall have a surface area of at least 50 m^2 (538 ft^2)… Shelters must be connected to the exterior of the tunnel by an access-way, which is protected from fire and intended for emergency purposes.
UK/BD78/99	3.16 … Single bore tunnel escape route and safe refuge requirements shall be examined and established by the Design Organization from first principles, to the agreement of the TDSCG.
NFPA 502 (2008 edition)	Not required
EU/2004/54/EC	2.3.3…. Examples of such emergency exits are… shelters with an escape route separate from the tunnel tube. 2.3.4 Shelters without an exit leading to escape routes to the open shall not be built.

TABLE F4-4
DIRECT PEDESTRIAN EXITS (NFPA 502*, 77*)

Country/ Guideline	Requirement
France/ Circ2000-63A2	2.2.1 In the case of tunnels where the roadway is less than 15 m (49.2 ft) from the ground surface …the facilities for the evacuation and protection of users and emergency access shall consist of direct communication with the exterior. Accessible to pedestrians only, these communication facilities must have a minimum width of 1.40 m (4.6 ft) and a height of 2.20 m (7.2 ft). …
Germany/RABT	2.5.1.3. The escape doors can connect directly to the open or to evacuation shafts, which are vertical structures for escape routes with stairways leading to the open. Stairways must be a minimum of 1.5 m (4.9 ft) wide. At the design of shafts the limited physical performance of disabled and elderly people will have to be considered.
UK/BD78/99	3.17 Tunnel cross connections are generally of three types: i…, ii…, iii. Access doors to a central escape shaft or passage, leading to a safe exit.
Netherlands/NL-Safe	11.4 Avoid staircases where possible. When necessary to provide, then minimum width: 0.7 m (2.3 ft)/minimum height: 1.9 m (6.2 ft).
NFPA 502 (2008 edition)	7.14.6.1 Emergency exits shall be provided throughout the tunnel spaced not more than 300 m (1,000 ft) apart. 7.14.6.2 The emergency exits shall be enclosed in a minimum 2-hour fire-rated enclosure having a Class A interior finish as defined in NFPA 101 (see also cross passages requirements).
EU/2004/54/EC	2.3.3… Examples of such emergency exits are…direct exits from the tunnel to the outside…

F5 Tunnel Incident Response

Appendix F5 provides comparison tables on tunnel incident response requirements in different national and international standards. It covers a Separate Emergency Vehicle Gallery Access (Table F5-1), Cross Passage Rescue Vehicular Access (Table F5-2), Emergency Lane (Table F5-3), Direct Pedestrian Emergency Access (lateral upstairs shaft) (Table F5-4), Turning Areas (Table F5-5), and Emergency Services Station at Portals (Table F5-6).

TABLE F5-1
SEPARATE EMERGENCY VEHICLE GALLERY ACCESS (NFPA 502)

Country/ Guideline	Requirement
NFPA 502 (2008 edition)	Not required
France/ Circ2000-63A2	2.2.2 In tunnels more than 5000 m (3.1 mi) long, which are not light traffic tunnels, the safety tunnel parallel to the tunnel or the access-ways providing access to the shelters must be capable of being used by the motor-driven equipment.
Germany/ RABT	2.5.1.3 In exceptional cases it can be reasonable to construct the evacuation tunnel so that it can be used by rescue vehicles. This may be relevant for tunnels longer than 300 m (984 ft) with high traffic load. The need for this arrangement shall be documented as part of safety concept.
Austria/ RVS	RVS 9.281 Could be used to minimize the ways for rescue staff. According to this, the tunnel category could be influenced.

TABLE F5-2
CROSS PASSAGE RESCUE VEHICULAR ACCESS (NFPA 502*, 56*)

Country/ Guideline	Requirement
France/ Circ2000-63A2	2.3.1…In tunnels more than 1000 m (3,280 ft) long, provision must be made at approximately every 800 m (2,625 ft) for the passage of emergency vehicles from one tube to the other if there are two tubes …
Germany/RABT	2.5.1.3. … For two tube tunnels every third cross passage can be constructed for the use of fire fighting and rescue vehicles, in case this is required by the safety and rescue concept. …
Austria/RVS	RVS 9.233 Dimension and design of cross passages. RVS 9.281 At every second emergency call station (a = 500 m or 1,640 ft) a cross passage for rescue staff vehicles is situated.
Korea	GIST: For tunnels over 500 m long or bi-directional tunnels with a parallel escape tube spacing for ambulances shall not exceed 750 m.
NFPA 502 (2008 edition)	Not required
EU/2004/54/EC	2.4.1 In twin-tube tunnels where the tubes are at the same level or nearly, cross connections shall be suitable for the use of emergency services at least every 1500 m (4,921 ft).

TABLE F5-3
EMERGENCY LANE (NFPA 502)

Country/ Guideline	Requirement
France/ Circ2000-63A2	2.1.1 - Emergency vehicle access widths. If traffic is one-way, the transverse profile must be designed to permit access by emergency vehicles, including in the normal traffic direction, when there are stopped vehicles on the nominal number of traffic lanes. Exceptions… if there is direct communication with the exterior… - if there is access to a second tube … and also if the traffic can easily be interrupted in the second tube…
Switzerland/ Design	In bidirectional traffic tunnels > 1.5 km (4,921 ft) emergency bays every 600 to 900 m (1,968 ft), alternating on each side, every 2 to 3 km turning bays (6,562 to 9,842 ft). Design of emergency bay.
Germany/RABT	2.5.1.1 Under certain economical and traffic conditions it can be reasonable to have an emergency lane—to be evaluated and documented… 2.5.1.2 Emergency bays shall be considered when the construction of emergency lanes is not reasonable. They are required at a tunnel length of 600–900 m (1,968 to 2,953 ft)… The distance shall be ≤ 600 m (1,968 ft) in each traffic direction.
Austria/RVS	RVS 9.232 Necessity and dimensions of emergency lanes in accordance to speed, traffic volume, number of lanes, and traffic regulation systems. RVS 9.233 Dimension and design of lay by. RVS 9.281 Lay by a = 1000 m (3,280 ft), in tunnels with two directional traffic on both sides, positioned together with emergency call.
NFPA 502 (2008 edition)	Not required
UK/BD78/99	3.14 Due to the high costs involved there are very few examples of continuous emergency stopping lanes within tunnels. However, additional lane width or widened verges provide a temporary expedient for traffic to be able to pass a stranded vehicle…. The first priority and whole basis of safe tunnel operation must always be to remove, as a matter of urgency, any obstacle to unrestricted lane use. Normal provision for tunnel class AA, A, B.

TABLE F5-4
DIRECT PEDESTRIAN ACCESS (LATERAL, UPSTAIRS, SHAFT) (NFPA 502)

Country/ Guideline	Requirement
Netherlands/NL-Safe	11.3 To support the rescue teams it is strongly recommended to locate the escape doors (from two tubes to the escape tube in the middle) opposite to one another. Appendix: The width of escape routes is based on width of the stretcher with a nurse accompanying on the side. The width of the doors must support easily the width of the stretcher.
EU/2004/54/EC	2.3.3 Emergency exits allow tunnel users to leave the tunnel without their vehicles and reach a safe place in case of an accident or a fire and also provide an access on foot to the tunnel for emergency services. Examples of such emergency exits are: direct exits from the tunnel to the outside, cross connections between tunnel tubes, exits to an emergency gallery, shelters with an escape route separate from the tunnel tube.

TABLE F5-5
TURNING AREAS (NFPA 502*, 56*)

Country/ Guideline	Requirement
France/ Circ2000-63A2	2.3.1…In tunnels more than 1000 m (3,280 ft) long, provision must be made at approximately every 800 m (2,625 ft) for… them to turn round…
Switzerland/ Design	In bidirectional traffic tunnels > 1.5 every 2–3 km turning bays.
Germany/RABT	2.5.6 Turning bays are standard equipment for tunnels > 900 m (2,953 ft), to be considered for tunnels 600 to 900 m (1,968 to 2,953 ft).
Austria/RVS	RVS 9.233 Dimension of turning areas. RVS 9.281 In category III and IV tunnels (see 4.4) with two-directional traffic, a turning area is necessary instead of each fourth lay by. Alternatively an escape tube for vehicles could be situated.
Norway/Road Tunnels	408.1 …Turning bays are arranged in tunnels with contra flow traffic. Lay bys function as turning bays for cars. Turning bays for larger vehicles are arranged as specified in figures… Normal distances between turning bays (for large vehicles) in class B, C and D are 2000 m (6,562 ft), 1500 m (4,921 ft), and 1000 m (3,280 ft).
Korea	GIST: For tunnels over 1000 m long, spacing between turning areas shall not exceed 750 m. Emergency stopping lanes can be used as turning areas.
NFPA 502 (2008 edition)	No requirements
UK/BD78/99	3.19 *Turning Bays*: In tunnels of over 5 km (3.1 mi) length, turning bays of sufficient size to enable a truck to turn around shall be provided, not more than 1 km (3,280.8 ft) from the middle of the tunnel. To be considered in class AA.

TABLE F5-6
EMERGENCY SERVICES STATION AT PORTALS (NFPA 502)

Country/ Guideline	Requirement
France/ Circ2000-63A2	2.3.2 A location 12 m (39.4 ft) long and 3 m (9.8 ft) wide for parking an emergency vehicle shall be provided outside, close to the ends… In addition to this … an arrangement enabling emergency vehicles to turn around/move from one roadway to another shall be provided externally, close to the portals.
UK/BD78/99	3.20 *Emergency Services Parking*: If necessary, an area close to the tunnel portals shall be provided for the parking of police and emergency services vehicles and equipment when attending a tunnel incident.

APPENDIX G

Past Tunnel Fires Description

G-1 TUNNEL FIRES IN THE US

WALLACE

Location: Wallace Tunnel, I-10, Mobile, Alabama
Date: late 1970s
Type: Medium

Conditions at Ignition: 2 a.m. in very light traffic. Engine fire from broken fuel line in camper truck. Electric fuel pump fed fire after engine turned off. Owner abandoned vehicle.

Detection/Alarm/Notification: Operator noted fire on TV monitors, activated traffic-control red lights, and summoned fire department.

Response: Fire equipment arrived within expected period. Very light traffic effectively stopped at portal. Ventilation system left inactive per fire department instructions. Tunnel filled with smoke; fire department unable to reach site of fire.

Control/Extinguishment/Suppression: None

Survival/Damage: Vehicle completely consumed; minor damage to tunnel; no injuries.

Source of Information: Study interview

CALDECOTT

Location: Caldecott Tunnel, US-24, Oakland, California
Date: 7 April 1982
Type: Major hazardous material

Conditions at Ignition: Probably inebriated westbound driver lost control of compact auto just past midnight in light traffic. Multiple glancing collisions with curbs and wall; stopped in left-hand lane just into straightaway from right-hand curve probably to inspect damage or affect minor repairs. At least two possibly three or more cars pass on right during next few minutes. Slightly speeding empty bus unaware of obstacle tries to pass full gasoline truck/trailer combination, as truck passes stopped auto, multiple collisions occur. Trailer tank ruptures; spilled gasoline ignites. Bus driver ejected by collision forces; bus continues, exits portal approximately 36 seconds after impact. Truck driver brings rig to stop, exits west portal on foot. As many as twenty cars enter east portal.

Detection/Alarm/Notification: Tunnel crew note noise and vibration from tunnel, see bus exit portal and come to rest against bridge pier (40 seconds after tunnel accident). Operators dispatched to investigate, two go to east portal; one inspects bus then drives east up westbound tube (1 minute, 40 seconds). Console operator receives call from tunnel reporting "bunch of accidents"; connection lost before more information is exchanged (1 minute, 10 seconds). Console operator notes multiple simultaneous phone calls from tunnel seconds before entire system fails. Operator driving east up tunnel finds burning gasoline truck, must retreat to west portal to find operating emergency phone (5 minutes minimum on operator's estimate). Console operator places first unambiguous call to Oakland Fire Department 7 minutes minimum after collision, as much as 10 minutes after original stoppage in left lane of tunnel. Alarm sounds at fire station 55 seconds after initiation of call.

Response: First pieces of fire equipment reach west portal 3 minutes 45 seconds after alarm (10 minutes, 45 seconds minimum after collision). First pieces of fire equipment reach east portal 7 minutes after alarm. Fire equipment from Orinda Fire Department reaches east portal 12 minutes after console operator's call. Oakland responds with seven engines (28 men), two chief's cars (four men), and three other units (eight men). Exhaust fans, which may have activated automatically during early stages of fire in response to high levels of CO sensed in tunnel, soon automatically shut down without having affected events or conditions in the tunnel.

Mother and grown son following bus in pickup witness collision between bus and gasoline truck, come to stop, notice small fire, back up but abandon pickup for fear of rear end collision. Mother calls on emergency phone (1 minute after collision) until phone malfunctions; returns to pickup less than 50 ft (15.2 m) from unmarked cross-adit to next tube. Son walks east in tunnel to warn motorists; approximately two minutes later enveloped by smoke; gropes way out last 200 ft (60.9 m) to portal. Truck driver and passenger remain with beer truck less than 150 ft (45.7 m) from unmarked cross-adit. Man in second pickup backs up when warned by son until enveloped by smoke near sedan with elderly couple, abandons vehicle and gropes remaining 80 ft (24.4 m) to portal. All other vehicles clear tunnel backing out, either through impatience or prompted by sight of approaching smoke wall. Tunnel fills completely with smoke in excess of 300°F (148.9°C) within 3 minutes of collision eastward from burning gasoline truck to portal.

Control/Extinguishment/Suppression: Natural draft eastward through tunnel blows all combustion products in that direction; firemen approach to within 75 ft (22.9 m) of fire, make no attempt to suppress fire at that time. Fans left off through concern for maintaining natural draft. Firemen unable to operate the valves that became corroded, in order to direct water-gasoline mixture in tunnel drainage away from nearby lake; concentrate on explosion and pollution hazard at lake while waiting for fire to burn down. Extinguishment efforts started at 1:29 a.m. (75 minutes after initial collision), tunnel water pressure falls too low to support hose streams. Firemen near tanker observe water leaking from damaged hose connections. Residual gasoline fire extinguished using foam and dry powder. Fire under control at 2:54 a.m.

Survival/Damage: Seven fatalities (auto driver, bus driver, mother, beer truck occupants, elderly couple), two hospitalized for smoke inhalation (son and pickup driver). Six vehicles totally destroyed in tunnel, one in collision with bridge pier. Tunnel suffered extensive superficial damage to walls, ceiling, and roadway. Most tunnel support systems destroyed or severely damaged, including lighting, emergency phones, signs, alarms, wiring, commercial broadcast antenna, and firefighting water supply. Repair costs estimated in excess of three million dollars.

Source of Information: Oakland Fire Department report, information transmitted with R. E. Graham (Chief, Maintenance Branch South, Caltrans) letter of 21 May 1982 to National Transportation Safety Board, and California Highway Patrol Accident Report.

Description of Facility

- Length: 3,370 ft (1027.2 m)
- Cross Section: 3 bores

2 unidirectional lanes each bore, middle bore is reversible.

- AADT: 304,000 (October 1, 2001)

Description of Incident

At 12:14 a.m. on April 7, 1982, a westbound driver lost control of his vehicle just past midnight in light traffic. He was probably inebriated. After multiple glancing collisions with curbs and the wall, He stopped the vehicle in the left-hand lane in the straightaway after a right-hand curve to inspect damage or attempt repair. A slightly speeding empty bus tried to pass a full gasoline truck/trailer combination at the same time the truck was passing the stopped vehicle. Multiple collisions occurred. The truck/trailer tank ruptured and the spilled gasoline ignited. The bus driver was ejected by the force of the collision and the bus continued through the tunnel, exiting the west portal about 36 seconds after impact. The truck driver stooped the truck/trailer and exited the west portal on foot. Up to 20 vehicles entered the east portal.

Tunnel crew saw the bus exit the tunnel and sent operators to investigate. One operator inspected the bus and drove east into the tunnel. The console operator received a call from the tunnel reporting a bunch of accidents, but the connection was lost. The console operator received multiple simultaneous phone calls from the tunnel seconds before the entire system failed. The operator driving east into the tunnel found the burning gasoline truck and had to retreat to the west portal to find an operating emergency phone. The Oakland Fire Department was called a minimum of 7 minutes after the collision.

Exhaust fans which may have activated automatically during the early stages of the fire in response to high level of CO, automatically shut down without having affected condition in the tunnel. A natural eastward draft through the tunnel blew all the combustion products in that direction. Ventilation fans were left off in an attempt to maintain the natural draft. The tunnel filled completely with smoke within 3 minutes of the collision.

Firefighters approached to within 75 ft (22.9 m) of the fire, but made no attempt to suppress it at that time. Firefighters were unable to operate corroded valves to direct the water-gasoline mixture in the tunnel drainage system away from a nearby lake. Firefighters concentrated on the explosion and pollution hazard at the lake while waiting for the fire to burn down.

At 1:29 a.m., efforts to extinguish the fire started. Water pressure in the tunnel fell too low to support hose streams. Firefighters near the tanker observed water leaking from damaged hose connections. The residual gasoline fire was extinguished using foam and dry powder. The fire was under control by 2:54 a.m.

There were 7 fatalities and 6 vehicles were totally destroyed in the tunnel. At least 3 fatalities were within 150 ft (45.7 m) of unmarked cross-connections to the adjoining tunnel. The tunnel suffered extensive superficial damage to walls, ceiling, and roadway. Most tunnel support systems were destroyed or severely damaged. These included: lighting, emergency phones, signs, alarms, wiring, commercial broadcast antenna, and fire fighting water supply.

This front to rear collision of bus, car, and fuel tanker incident was created by limited sight conditions within the tunnel. The limited sight distance in the Caldecott Tunnels was due to narrow 2 ft (0.61 m) wide shoulders and a 2,400 ft (731.5 m) radius curve in the alignment. The stopping sight distance calculated from these conditions is only 415 ft (126.5 m) at a safe stopping speed of 50 mph (80.5 km/h). The safe stopping speed is the speed at which a vehicle would safely stop within the available sight distance.

<u>BALTIMORE HARBOR</u>

Location: Baltimore Harbor Freeway, Baltimore, Maryland
Date: 23 March 1978
Type: Major hazardous material

Conditions at Ignition: Soft drink delivery truck rams fuel oil tanker from behind in heavy traffic one-quarter mile (0.4 km) after exiting east portal of Baltimore Harbor Tunnel. Fuel spilled from soft drink truck ignites and spreads to tanker. Third truck carrying creosoted railroad ties also ignited.

Detection/Alarm/Notification: Unknown; tunnel personnel not involved.

Control/Extinguishment/Suppression: Fire department put out fire in unspecified short period.

Survival/Damage: Unknown, none to tunnel. Traffic congested around Baltimore metropolitan area throughout afternoon and evening.

Source of Information: Study interview.

<u>HOLLAND</u>

Location: Holland Tunnel, New York City, New York
Date: 13 May 1949
Type: Major hazardous material.

Conditions at Ignition: Fully enclosed trailer carrying eighty 55-gallon (208.2 L) drums of carbon disulfide enters New Jersey portal of tunnel, in violation of Port Authority regulations and allegedly non-placarded in violation of ICC regulations, in very heavy, slow traffic approximately 8:30 a.m. Drum breaks free and ignites upon striking roadway approximately 2,900 ft into tunnel. Truck rolls to stop in left lane. Four trucks catch fire or are abandoned adjacent to trailer in right lane. Five additional trucks stopped 350 ft (106.7 m) to the rear grouped tightly in right lane also ignite. Approximately 125 automobiles, buses, and trucks fill both lanes back to New Jersey portal.

Detection/Alarm/Notification: Patrolling officer 100 ft (30.5 m) from mishap transmits trouble signal to control room at 8:48 a.m.; assists drivers escaping scene through cross-adit to north tube. First fire alarm transmitted by patrolling officers further east at 8:56 a.m., who then run to assist. Tunnel personnel in tunnel west of fire promptly evacuate occupants on foot to New Jersey; start backing vehicles out of tunnel. Jersey City Fire Department receives telephone notice at 9:05 a.m. New York Fire Department receive fire alarm at 9:12 a.m.

Response: Three-man emergency crew drive west through eastbound tube on wrecker and jeep upon receiving 8:56 a.m. fire alarm; commence fighting fire with 12 in. (30.5 cm) hose and spray nozzle. Assist two tunnel patrolmen overcome by smoke. Knock down fires in two trucks of eastern group; tow one to New York portal. New York rescue company and battalion chief drive west through westbound tube; cross to scene at adit and relieve tunnel emergency crew. Some firemen in distress recover by breathing at the curb-level fresh air ports.

Second alarm transmitted at 9:30 a.m. activates four engine companies, two ladder truck companies, and a water tower. Firemen not involved in firefighting search through burning trucks, help three trapped people to safety. Additional NYC pumpers augment capacity of tunnel fire main; activate five 22 in. (55.9 cm) hoses and a foam generator. New Jersey engine company, truck company, rescue company, and battalion chief transmit second alarm upon initial inspection at New Jersey portal. Oxygen masks ordered.

Firemen establish hose lines through half mile (0.8 km) of abandoned vehicles; extinguish fires in second group of trucks. Tunnel ventilation accelerated to full capacity at fire site at approximately 9:45 a.m.; firemen discover they can work without masks. Two exhaust fans disabled by heat at 1000°F (537.8°C); third fan kept in service by water spray. Ceiling at fire collapses; fire boats monitor Hudson River above for signs of tube failure.

Remaining non-burning vehicles removed by 10:15 a.m.; JCFD drives two pumpers east to fire site, joining forces with NYFD. Fire controlled by approximately 1:00 p.m.; overhauling operations continue until 12:52 a.m. the next morning. Residual carbon disulfide and turpentine reflash at 6:50 p.m. during cleanup; extinguished with 5-gal. (18.9 L) foam extinguishers; area then covered with heavy foam.

Total equipment involved: one tow truck, several jeeps, seven chief units, five rescue companies, seven police emergency squads, 14 engine companies, six truck companies, one lighting truck, one water tower, one smoke ejector, one foam truck, 40 additional firemen, at least 13 ambulances at the scene, and four Consolidated Edison emergency trucks with inhalators (total of 29 firefighting units, 20 medical units, seven supervisory units, at least three port authority vehicles, and four commercial vehicles with special apparatus on board. Unknown total number of personnel in excess of 250).

Survival/Damage: Ten trucks and cargoes completely destroyed, 13 others damaged. 600 ft (182.9 m) of tunnel wall and ceiling demolished; walls spalled in places to cast iron tube plates. 650 tons (589,670 kg) of debris removed from tunnel. Tube reopened to traffic 56 h after fire started. All cable and wire connections through tube disrupted at fire. Total damage estimated at $1 million dollars (in 1949 dollars). Sixty-six injuries, 27 requiring hospitalization; no fatalities.

Source of Information: The Holland Tunnel Chemical Fire report by the National Board of Fire Underwriters.

One recalls trapped firefighters breathing from the curb-level fresh air inlets in Holland Tunnel fire.

SQUIRREL HILL

Location: Squirrel Hill Tunnel, Pittsburgh, Pennsylvania
Date: Unknown
Type: Medium

Conditions at Ignition: Private auto abandoned and set afire in deserted, early morning tunnel.

Detection/Alarm/Notification: Fire eventually discovered by unspecified means. Fire department summoned by unspecified means.

Response: Local fire department responded with unspecified resources.

Control/Extinguishment/Suppression: Fire extinguished without incident.

Survival/Damage: Vehicle destroyed. No damage to tunnel. No injuries.

Source of Information: Study interview.

BLUE MOUNTAIN

Location: Blue Mountain Tunnel, Pennsylvania Turnpike, Franklin County, Pennsylvania
Date: 1965–1966
Type: Medium

Conditions at Ignition: Truck carrying fish oil (not considered hazardous material at the time) caught fire in tunnel.

Detection/Alarm/Notification: Unknown.

Response: Fire department responded to unspecified degree.

Control/Extinguishment/Suppression: Fire extinguished without incident; combustion products left tunnel without mechanical assistance.

Survival/Damage: Unspecified damage to truck. Minor if any damage to tunnel. No injuries specified.

Source of Information: Study interview.

CHESAPEAKE BAY

Location: Chesapeake Bay Bridge/Tunnel, Norfolk, Virginia
Date: 3 April 1974
Type: Medium

Conditions at Ignition: Six-wheel closed refrigeration truck blows left rear tire and careens out of control down grade in south tunnel, contacts curb and overturns, blocking both lanes. Full, 50-gal. (189.3 L), fiberglass fuel tank explodes in flames upon overturn.

Detection/Alarm/Notification: Mid-tunnel booth patrolman hears blowout, observes overturn and explosion, reports "accident with fire" to control booth at 12:18 p.m.

Response: Booth patrolman moves to scene; assists driver and directs him to safety; halts oncoming traffic. Tunnel emergency trucks dispatched from two shoreward portal islands at 12:19 p.m. Three other tunnel units in transit on bridge also converge. Chief of Police arrives at 12:21 p.m., finds Virginia State Trooper unit already giving aid to injured driver and crew of north emergency truck already fighting fire with hose and foam. Additional alarm placed to Chesapeake Beach Fire Department, who responded with one engine, one rescue unit, and one ambulance. Flush truck and maintenance wrecker also summoned.

Control/Extinguishment/Suppression: Fuel fire brought under control within six or seven minutes; secondary fires extinguished soon after. Some dense smoke hung in area during fire, but breathing apparatus not required. Exhaust fans operated throughout fire. Internal telephone system required since fire destroyed overhead antenna. Driver conveyed to hospital by 12:50 p.m.

Survival/Damage: Truck essentially destroyed; cargo undamaged. Tunnel ceiling tiles, hand rail, and antenna wire damaged by impact or fire, value unspecified. Tunnel reopened to traffic at 4:50 p.m. One injury, driver hospitalized in shock with burns on arms and legs.

Source of Information: Memoranda of booth patrolman and Chief of Police sergeant of 5 April 74 concerning Economy Stores, Inc., truck accident/fire.

One of the parameters for risk analysis is the cost of life, which varies in different countries. In 2009, the federal government (*78*) calculated the value of one life in the U.S. to be worth \$5.8 million when deciding the benefits of railroad construction to ensure increased workers' safety. A person that dies without newly mandated safety rules is referred to as a "statistical life" by government analysts, who compare costs and benefits of new programs. The value of each of those lives range from \$1 million to \$10 million.

The Federal Railroad Administration estimated each life to be worth \$5.8 million when analyzing new safety rules to prevent construction workers from being hit by trains that are being built or repaired. The new rules are in response to the seven U.S. workers who have been killed under those circumstances since 1997 (*78*).

G-2 TUNNEL FIRES DESCRIPTION—OUTSIDE THE U.S.

Nihonzaka Tunnel, Japan (1979)

The Nihonzaka Tunnel is located half way between the cities of Tokyo and Nagoya. The tunnel consists of two approximately 2 km (1.24 mi) long tubes, which are operated in each direction. There were no restrictions on hazardous materials traveling through the tunnel until the fire occurred.

The fire was started on July 11, 1979, by a rear-end collision involving 4 trucks and 2 cars. The accident caused tanks on the vehicles to become leaky so that fuel (gasoline and diesel) leaked out. This fuel ignited and thereby triggered a conflagration affecting 173 vehicles in total.

Among the burnt-out vehicles there were two road tankers carrying neoprene and accompanying solvent. The load on another truck involved in the accident consisted of 10 drums of ether. These also became leaky as a result of the accident. The ether which leaked out immediately began to burn intensely. Other materials which burnt were artificial resin and plastics.

The deluge sprinklers located in the tunnel were set off automatically by fire alarm systems. After approximately 10 minutes the fire appeared to have been extinguished. However, approximately 15 minutes later the fire flared up again. This produced thick black smoke. Thereafter the fire grew to a length of more than 1100 m (3,609 ft).

Although there was a message at the portal of the tunnel that there had been an accident, vehicles continued to drive into the tunnel. A tailback of 231 vehicles formed in front of the source of the fire.

The Nihonzaka Tunnel is monitored from two control centers (Shizuoka and Kawasaki). The fire was first noticed by the Kawasaki control room. Mistakenly, from here the fire service responsible for the Shizuoka district was alarmed initially, although it was further away. A unit of the fire service which was much closer was only informed 40 minutes after the fire broke out.

The people inside the tunnel initially tried to extinguish it themselves by rolling out the hoses attached to the hydrants in the emergency areas. However they were not able to activate the extinguishing water supply, as they were not aware that in addition to the throwing of a lever—which is normally sufficient—it was also necessary to press a button. Personnel located in the Shizuoka control centre failed in their attempts to reach the scene of the accident, but were able to assist 42 vehicles in escaping from the tunnel.

At around 8:30 p.m. 208 people had managed to escape from the tunnel on foot (approximately 15 minutes after the fire had broken out again). The firemen reaching the scene of the fire could not initially achieve a great deal, as their respiratory equipment only allowed each of them to work for 30 minutes.

The supply of fire-fighting water in the tunnel (approximately 170 m^3 or 45,000 gal.) had been used up approximately 1½ hours after the fire started without it being possible to put the fire out.

When the fire-fighting water ceased to flow, combustible gases and vapors drifted from the source of the fire to two groups of vehicles in the tunnel, setting them alight.

The extinguishing work could only be resumed after a "shuttle service" to surface waters had been set up using 7 sets of fire-fighting appliances. It was only possible to bring the fire under control 2 days after it had broken out. The fire, which initially started on July 11, 1979, was finally extinguished on July 18 (i.e., approximately one week after the rear-end collision).

During the fire the semi-transverse ventilation of the tunnel worked in the suction mode at full power. However this was not sufficient to extract enough smoke and hot burning gases for the fire service units, who were equipped only with limited respiratory protection, to effectively fight the fire.

Of the 230 vehicles in the tunnel, 173 were destroyed by the fire; 7 people died in the fire, while a further 2 were injured.

The tunnel lining and the additional 4.5 mm (0.177 in.) thick reinforcement of the tunnel walls were damaged for a length of approximately 1100 m (3,609 ft). The greatest damage occurred in an area of approximately 500 m (1,640 ft) on either side of the fire source. The road surface melted in places up to a depth of 2 to 3 cm (0.79 to 1.18 in.) on average, with the maximum depth being approximately 7 cm (2.76 in.). Electric cables and pipes lay in a cable duct in the road surface concrete continued to function normally.

During the repair work the concrete of the tunnel lining was removed up to a depth of approximately 3 cm (1.18 in.). Then wire grating was placed in position and steel fiber concrete injected using the dry injection method. The application thickness depended on the damage to the tunnel, being approximately 5 to 10 cm (1.97 to 3.94 in.) on average.

After the repair work to the roadway had been completed on August 7, work began on repairing the tunnel equipment. This work lasted approximately 1 month, including among other things:

1) Renewal of the surveillance and fire alarm systems
2) Reconstruction of the ventilation system
3) Renewal and supplementation of the fire extinguishing equipment
4) Installation of a guided escape system (including loudspeakers)

NIHONZAKA

Location: Nihonzaka Tunnel Shizuoka Prefecture, near Yaizu City, Japan (100 miles or 161 km southwest of Tokyo) correct Japanese pronunciation: Nee-hon-za-ka, without stress. "Nihon" is the Japanese name for their post-WWII nation.
Date: 11 July 79 (Wednesday)
Type: Major hazardous material

Conditions at Ignition: Four large trucks and two autos involved in collision three-quarters through westbound tube; spilled fuel ignited at 6:39 p.m. 231 vehicles are in tunnel behind fire or enter tunnel unheeding or in contravention to emergency warnings at east portal.

Detection/Alarm/Notification: Operators notice smoke in tube on TV monitors, display 'OFF LIMITS' sign at east portal, reverse ventilation system, and notify Shizuoka Fire Department, behind fire, at 6:42 p.m. Yaizu City Fire Department, in front of fire and much closer to tunnel, summoned at 7:18 p.m. Automatic spray heads interlocked with fire detector activate at accident site.

Response: Motorists at scene deploy hoses from hydrant boxes, but cannot activate water since valves require the pushing of an operating button in addition to traditional turning of handle. Shizuoka equipment at east portal at 6:48 p.m. unable to reach accident site, assist 42 vehicles to escape tunnel. Automatic spray system reportedly suppresses fire at initial site at 6:50 p.m., but fire reignites at 7:20 p.m. 208 occupants of vehicles trapped in tunnel escape on foot out east portal by 8:30 p.m. Three Yaizu City engine companies arrive and augment fire main at FD connections at west portal.

Control/Extinguishment/Suppression: Initial efforts consume entire 40,800 gallon (155,000 L or 40,947 gal.) water supply by 8:05 p.m. (1 hour, 26 minutes after automatic spray heads activate) without extinguishing fire. Unburned combustible vapors from accident site spread fire to two other groups of vehicles in tunnel when water supply is exhausted. Suppression resumed with water relayed from unspecified natural sources. Fire under control Friday afternoon but continued burning until 10:00 a.m. 18 July, nearly a week after initial incident. Semi-transverse ventilation system, with reversible supply fans only, operated in exhaust mode (maximum exhaust capacity one-half rated supply capacity) throughout emergency but was unable to clear heat and smoke enough to allow breathing-apparatus-equipped firemen to work effectively in tunnel. Total equipment and personnel involved: 34 engines, 2 portable fire pumps, 30 (10 ton) tank trucks, three ambulances, 654 personnel.

Survival/Damage: Of 231 vehicles including 66 trucks in tunnel during course of incident, 58 are undamaged, 173 destroyed. Ceiling, walls, and tunnel systems almost completely destroyed for central 1145 m (3,756.6 ft). Seven fatalities, six in collision and one of injuries suffered in collision; two other unspecified injuries. "Police and sufferers will take matter into court," ends summary report.

Source of Information: Tokyo Fire Department letter to Hamburg, West Germany, Fire Department of 30 August 79; Summary of Automobile Fire in Nihonzaka Tunnel, of unknown source but written in English by a Japanese; and National Bureau of Standards Memorandum for the Files by D. Gross of 26 September 79 concerning visit to test facilities in Japan.

Summary:

1) The fire was caused by a rear-end collision.
2) The deluge sprinklers located in the tunnel were set off automatically by fire alarm systems. After approximately 10 minutes the fire appeared to have been extinguished. However, approximately 15 minutes later the fire flared up again. This produced thick black smoke. Thereafter the fire grew to a length of more than 1100 m.
3) The fire department alarm was incorrect (wrong fire department, too late).
4) Those people in the tunnel could not use the fire extinguishers as the instructions were not clear.
5) The efforts of the fire department to extinguish the fire were considerably hampered by the inadequate respiratory protection devices.
6) The suction power of the semi-cross ventilation system in the tunnel was not sufficient to extract the smoke and hot burning gases.
7) The hot burning gases caused the fire to jump between groups of vehicles.
8) In the fire 7 people died, the tunnel was damaged over a length of approximately 1,100 m (3,609 ft) and 173 vehicles were destroyed.

MOORFLEET

Location: Moorfleet Tunnel, Hamburg, West Germany
Date: 31 August, 1969
Type: Major hazardous material

Conditions at Ignition: Driver of truck trailer combination carrying 14 tons of polyethylene stopped in cut-and-cover tunnel at 1:10 a.m. probably to inspect malfunction by tunnel illumination. Discovered burning tire on trailer, uncoupled and drove tractor out of tunnel.

Detection/Alarm/Notification: Unknown

Response: Unknown

Control/Extinguishment/Suppression: Fire was extinguished using foam; water used to cool wreckage. Other details unspecified.

Survival/Damage: Uncaptioned pictures reveal damage to ceiling and walls similar to Caldecott and Holland Tunnel fires; no other details available

Seljestad Road Tunnel (Norway)
Description of Facility

- Length: 1,268 m (4,160 ft)
- Cross Section: Two 11 ft (3.35 m) lanes, undivided, bidirectional
- AADT: 1,350 vpd
- Trucks: 20%

The tunnel has normal lighting. There are four SOS stations, one at each end and two at 500 m (1,640 ft) intervals inside. Six hand-held fire extinguishers are located every 250 m (820 ft). Eight jet ventilators automatically run in the direction of the draft at any given time. The fans are started by signals from CO and NO_2 detectors. Flashing red warning signals are located at both ends of the tunnel. High-voltage and communications cables were in a concrete conduit along an enclosed ditch and a fiber optic communication cable was mounted on the ceiling. The tunnel is monitored and remotely operated from the Hordaland Road Traffic Centre in Bergen.

Description of Incident

At 8:52 p.m. on July 14, 2000, an accident occurred when two truck-trailers met about 300 m (980 ft) inside the tunnel. Because of narrow roadway, the two truck-trailers slowed to pass at low speed. Behind one truck-trailer, five following passenger cars also slowed. A truck-tractor approaching these passenger cars from behind was unable to slow down sufficiently resulting in a rear end collision involving all five cars. One of the vehicles immediately caught fire which spread to the other vehicles. A motorcycle and an additional passenger car were ultimately involved in the accident. Both truck-trailers escaped the accident and exited the tunnel.

Shortly after the fire started, a ceiling mounted communications cable burned, cutting off telecommunications in Roldal. Because of the cable failure, it was not possible to notify the Roldal fire department. This also cut communication and control with the Road Traffic Centre for emergency telephones and technical equipment inside the tunnel. The fans functioned automatically and technical functions could be controlled from a board installed outside the tunnel.

Due to the cable failure, the flashing red signals at the tunnel portals could not be activated shortly after the start of the fire. All traffic on the Roldal side of the tunnel was stopped after smoke was observed coming out of the tunnel. In addition, a bus was turned around and placed across the roadway to prevent additional traffic from entering the tunnel from the Roldal side. According to the Odda fire department, when arriving at the scene no manual control of technical installations was required because the draft was moving in the appropriate direction and because all traffic by that time had stopped. A total of eight vehicles were involved in an accident resulting in one of the vehicles catching fire. The fire spread rapidly to six other cares quickly filling the tunnel with smoke from the collision site all the way out to the east entrance. The accident was reported to the emergency services in Odda at 8:55 p.m. and the first unit arrived at the scene at 9:20 p.m. Occupants of the burning cars were able to get out of the tunnel on their own or with assistance from others. After the fire was extinguished a tunnel search with smoke evacuation crew located four persons alive in the proximity of an abandoned passenger car. There were no fatalities in the accident.

Tauern Tunnel
Description of Facility

- Length: 6,400 m (21,000 ft)
- Cross Section: Two-lane, undivided, bidirectional
- AADT 14,100
- Trucks: 26%

The tunnel near Salzburg, Austria, has a full transverse ventilation system split into four sections. The two outer sections supply and exhaust air through the tunnel portals. The inner sections supply and exhaust air through a ventilation shaft in the middle of the tunnel. Fresh air can be supplied at a rate of about 190 m^3/s per kilometer (390 CFM per lane foot). Exhaust air is removed at a rate of about 115 m^3/s per kilometer (235 CFM per lane foot). Exhaust openings are located in the ceiling every 6 m. The tunnel has an automatic fire detection system.

Description of Incident

At 4:47 a.m. on May 29, 1999 a fire resulted when a semi-truck laden with cows collided with four cars and a paint truck in front. The semi-truck driver had failed to stop either through sleep deprivation, driver error, or excessive speed.

The semi-truck smashed the cars behind the paint truck so thoroughly that the first personnel on the scene believed it to be only one car. Two of the four cars between the trucks had been pushed under the paint truck, while the two other cars were crushed into the tunnel wall. The trucks ended up nose to tail. Gasoline from the damaged vehicles is presumed to have ignited, starting the fire which led to explosions of the spray paint cans in the paint truck. The flames spread to a total of 16 trucks and 24 passenger cars were burned. Eight people died instantly during this collision while two escaped from one of the cars that had been crushed into the wall. Four people died in the subsequent fire. Two people had not left their car. The paint truck driver after having escaped, went back into the tunnel to retrieve some paperwork. He joined the two people who had stayed in their car and all three perished. Another truck driver suffocated while fleeing the accident scene. Three of his colleagues escaped by cramming themselves into an emergency call booth that was sealed tight enough to prevent the smoke from entering.

Events leading up to the collision included a traffic backup caused by an earlier serious accident north of the tunnel at 2:08 a.m. This produced a higher than normal volume of traffic. Night repair work being carried out in the Tauern Tunnel about 800 m (2,625 ft) from the northern portal reduced tunnel traffic to one lane. Alternating one-directional use was controlled with traffic signals. The Salzburg bound traffic was stopped during one of these stop and go sequences at the time of the collision.

At 4:50 a.m., the fire alarm system in the control room at St. Michael was triggered. The manager on duty at the control room switched to four cameras near the crash site, but nothing could be seen. Alarm status of the fire alarm system then switched the traffic lights at both tunnel entrances to red. Many people ignored the red traffic lights and entered the tunnel. Video cameras at the north portal showed thick smoke coming up the tunnel at high speed. As smoke quickly started to pour out of the north end of the tunnel, drivers were still entering from the south and disregarding the red traffic lights. The tunnel manager immediately contacted police and firefighters. From video feeds from the tunnel control room showed police that traffic had come to a stop and people were fleeing the tunnel by foot. The accident location forced fleeing motorists to run either 800 m (2,625 ft) toward the northern portal or 3.4 miles (5.5 km) toward the south portal At 4:53 a.m., the first hand held fire extinguishers located in the call booth niches were used. At 4:56 a.m., the ventilation system automatically switched over to fire mode. The north end exhaust ventilation extracted smoke at a rate of 230 m^3/s (487,370 CFM) upward into the exhaust air ducts. This caused a stratification of the smoke, so the smoke stayed at the ceiling for the first 10 to 15 minutes. This allowed about 80 people to escape.

The first firefighters arrived at the south entrance 27 minutes after the start of the accident fire. They drove slowly toward the accident even though the visibility was zero. A number of explosions then occurred which produced much more smoke and fire. The heat became so extreme that the firemen had to retreat to the nearest emergency phone niche. Some of the phones in these booths stopped operating. The smoke from these explosions started heading to the north portal in spite of the exhaust ventilation.

The tunnel electrical engineer arrived at the control room during this time and took manual control of the ventilation system. The commander of the firefighters gave the order to switch to maximum extraction in the fire portion of the tunnel while the other three ventilation sections received maximum fresh air. The third section ventilation system helped force the smoke out through the north portal.

This allowed firefighters to rescue three people trapped in an emergency niche for slightly more than an hour and to put out the fires in 15 to 17 burning vehicles. The firefighters could not penetrate any further northward due to the intense heat and smoke. The third section ventilation system was changed from supply to exhaust mode to help reduce some of the smoke exiting from the north portal.

At 6:00 a.m., more than 300 firefighters had been assembled at the tunnel entrances; 170 at the north entrance and 138 at the south entrance. They had at their disposal an assortment of equipment which included 2 infrared cameras, 23 light systems, a mobile generator, and 12 giant fans. This permitted the start of the fire fighting from the north portal.

At about 10:00 a.m. engineers believed that the tunnel was being weakened structurally by the fire. Before the northern firefighters could begin fighting their way through the inferno with 5 foam/water hoses, the engineers had to inspect and provide props to prevent the tunnel from collapsing. The heat inside the tunnel reached 2000°F (1093.3°C) at the impact and 1800°F (982.2°C) in a 700 m (2,300 ft) long stretch. The heat was so intense that the inside walls crumbled. The outside walls survived quite well.

At 3:00 p.m., firefighters started putting out the fire with a mobile foam thrower and by 9:00 p.m. the fire was finally extinguished. All told the casualty count came to 12 dead, 49 injured and 50 cattle destroyed. On January 10, 2000, another truck fire broke out in the Tauern Tunnel. Many of the same mistakes were made, but this time all managed to escape as firefighters put out the fire.

Traffic conditions due to construction at the time of the incident created a unique tunnel operating state that could not be anticipated under normal operations. It is important to note that motorists continued to enter the tunnel even after traffic signals indicated no entry. Special care is to be given to VMS design and accompanying changeable warning beacons to make traffic control more effective.

The ventilation was capable of keeping the smoke layer at the ceiling for 15 minutes. Subsequently, the fire energy overwhelmed the ventilation system and began pushing smoke along the length of the tunnel. After the fire was established, fire fighting operations of both people and equipment movement into the tunnel were extremely difficult due to uncontrolled backlayering of smoke in the tunnel. The smoke traveled down the tunnel corridor against the direction of the ventilation system.

St. Gotthard Tunnel
Description of Facility

- Length: 10 miles (16.3 km)
- Cross Section: Two-lane, undivided, bidirectional travel lanes with separate service tunnel
- ADT: 18,000

This tunnel is located in the Trico region of the Swiss Alps between the cities of Goeshenen and Alrolo. The tunnel has a parallel service/safety tunnel with connecting passageways every 250 m (820 ft) and an extensive network of smoke detectors. The service/safety tunnel is wide enough for people on foot, but not for service vehicles. Four firefighters are located at each entrance 24 hours a day. The ventilation system consists of fans and shafts that can replace the air in the tunnel every 15 minutes.

Description of Incident

At 9:30 a.m. on October 24, 2001, two trucks collided head-on about a mile (1.6 km) from the south entrance during a period of heavy traffic. The load of tires in one of the trucks burst into flames. The driver of this truck escaped by climbing out of the window. The burning tires emitted noxious fumes and made the fire difficult to extinguish. Temperatures were reported to be 1,200°C (2,192°F). The ventilation shafts helped expel the smoke and warning barriers were put up to prevent cars from entering the tunnel after the blaze started. The blaze burned for more than 48 hours.

Many drivers were able to back out of the tunnel or escape by foot through the service tunnels. All told there were 23 vehicles at the site of the collision, but only 11 people died. Some of the people who died in this accident had actually made it to safety, but had returned to their cars to retrieve items. Others had died because they had stayed in their cars while using their cell phones.

After the fire started, barriers automatically stopped more traffic from entering the tunnel and ventilators switched to emergency settings. Rescue workers arrived within minutes of the first alert. Firefighters worked their way to within 200 m (650 ft) of the accident and then had to use the service/safety tunnel to access the fire. A 100 m (330 ft) portion of the tunnel collapsed. The likely reason for the collapse was the spalling of the concrete due to conversion of moisture to steam. The concrete spalling exposed the structural steel reinforcing thus making it ductile. This combination led to the collapse. The tunnel was reopened on December 21, 2001.

The St. Gotthard Tunnel was originally designed for horse-driven carriages. The horses would get frightened when they saw the open end of the tunnels, so the tunnels were designed to curve. This configuration reduces the stopping sight distance in modern roadways. A significant number of fatalities were created by motorists returning to their cars to retrieve items. Clear instructions and signage could encourage safe evacuation patterns for tunnel occupants.

Mont Blanc Tunnel
Description of Facility

- Length: 11,600 m (38,000 ft)
- Cross Section: Two-lane, undivided, bidirectional
- AADT: 5,500
- Trucks: 40%

The Mont Blanc tunnel was built jointly by the French and Italians in 1965 and is operated by both nations. Each nation maintains one half of the tunnel although a larger portion of the roadway is on the French side.

Shelter rooms are located every 600 m (2,000 ft). These rooms are separated from the road tunnel, supplied with fresh air, and designed for 2-hour fire resistance. Each fresh-air duct supplies air at a rate of about 75 m^3/second to one-eighth of the tunnel length (16.5 CFM per lane foot). Exhaust air is removed at a rate of about 300 m^3/second per kilometer (95 CFM per lane foot). Fresh-air openings are located near the bottom of the walls at approximately 10 m (30 ft) intervals. One square-meter (10.5 ft^2) exhaust openings are located near the ceiling at about 300 m (980 ft) intervals.

Description of Incident

At 10:53 a.m. on March 24, 1999, a refrigerated truck caught fire for unknown reasons. The truck was traveling in the France–Italy direction. The toll collector noticed nothing unusual, but truck drivers from the opposite direction used their headlights to warn the driver that something was wrong. He could see smoke coming from underneath his truck when he looked in his rear-view mirrors. He slowly stopped the truck at Rest Area 21 located 6,700 m (21,981.6 ft) from the entry toll plaza. He could not get to his fire extinguisher in the cab of the truck, because the fire had started to engulf the cab. He fled on foot toward the Italian portal.

The smoke was observed on the monitor screens at the time the truck stopped, but the obscuration monitors on the French side and the heated gas monitors on the Italian side both failed to trigger an alarm while the truck was moving. The French monitors belatedly indicated higher than normal temperatures.

Italian authorities were notified of the fire at 10:54 a.m. by a phone call from a person at Rest Area 22. It was confirmed when they received an alarm from a fire pull box at 10:57 a.m. and the removal of a fire extinguisher at 10:58 a.m. at Rest Area 21. At 10:55 a.m., all traffic signals in the French–Italy direction turned red. The Italian entrance was closed at 10:56 a.m.

The spread of the fire was not affected by the contents of the truck which contained margarine and flour and was not classified as hazardous cargo. However, the refrigerated trailer was fitted with a thermal insulation foam that was highly flammable. The cause of the fire is suspected to be overheating of the engines and turbos due to the long and difficult uphill drive. The wind at the start of the fire was coming from the Italian side, but the wind shifted before other emergency vehicles could reach the fire. Due to the extremely rapid spread of the fire, emergency vehicles could not get to the site of the collision in time to control the fire as had been done with prior accidents in this tunnel.

The video monitors indicated that the smoke spread from ceiling to floor and did not stratify to allow people to escape by staying low to the road. Thirty-four people died in their vehicles without fleeing through the tunnel or finding refuge in the fresh air supply openings. This indicated that they were not aware of the dangerous situation that existed. Contributing to this was the fact that they could not see the problem ahead of them due to large trucks blocking their view. When the smoke did reach them, they apparently stayed in their cars because the cars provided a sense of security. The ventilation supply and exhaust ducts attempted to control the smoke. When the alarm went off most of the supply ducts started delivering air at full levels.

The French side activated the 2000 or 4000 m (6,561.7 to 13,123.4 ft) reversible duct nearest to the fire to exhaust air. The Italian side left the reversible duct positioned to supply air and set it at maximum capacity. At 11:15 a.m., the Italian operators tried to switch to exhaust with an automatic system geared to concentrate the exhaust flows near the site of the fire and later at 12:30 and 12:45 they tried manually to do this same task. Neither the automatic or manual change over to the exhaust mode was successful. The smoke never exhausted. The French and the Italians did not have a centralized management system to indicate the total power usage per fan, but they do know the total power usage by all fans.

It took 53 hours to extinguish the fire. The fire cost the lives of 39 people, including 29 inside vehicles and 9 found outside. Thirty-four vehicles, including 20 trucks were burned. The fire damaged over 900 m (2,952.8 ft) of the tunnel structure and a considerable amount of tunnel equipment. The tunnel reopened March 9, 2002.

This fire incident was probably initiated by equipment temperatures on board a freight truck. Overheating would be due to mountain pass driving conditions contributing to ignition and combustion.

Main lessons learnt from the Mt. Blanc and Tauern Tunnel fires of 1999

The Mont Blanc and the Tauern tunnels are both bidirectional and transverse ventilated. As the fire in the Tauern tunnel involved a heavy goods vehicle transporting lacquer tins, and because there were more people present in the Tauern tunnel, this fire was potentially more serious than the Mont Blanc fire. The heat release rate of both fires reached quickly high values.

However, the outcome in terms of loss of life for the Mont Blanc fire was far more serious than for the Tauern fire. Several differences between these two fires may have contributed to the outcome in each case. From a human behavior view, the Tauern tunnel fire occurred shortly after the Mont Blanc catastrophe, and so the people involved were well aware of the possible severe consequences that could result from a tunnel fire and so fled the fire almost immediately. In addition, in the case of the Tauern fire, the fire was located “near” one of the tunnel portals adding evacuation. In the Mont Blanc Tunnel fire, the fire occurred almost in the middle of the tunnel compounding the difficulties with both smoke extraction and evacuation. Furthermore, the two separate control centers within the Mont Blanc tunnel made managing the fire difficult.

Other aspects that contributed to the differences in these two situations are given by the fact that the ventilation system of the Tauern Tunnel had a higher performance than the one in the Mont Blanc Tunnel, and the firefighters in the Tauern Tunnel were better equipped than those in the Mont Blanc Tunnel (see Table 61).

Pfänder Tunnel, Austria (1995)

On April 10, 1995, there was a traffic accident in the tunnel as a result of which three vehicles burnt out. The fire was located approximately 4.3 km (2.67 mi) from the northern portal and 2.4 km (1.5 mi) from the southern portal. The accident was caused by the microsleep of a car driver traveling in a southerly direction. He crossed over to the oncoming traffic lane and crashed into an articulated vehicle laden with bread. This truck began to skid, then crossed over to the wrong side of the road, slid along the tunnel wall for approximately 130 m (426 ft) and then finally

TABLE G1
EVENT, CONSEQUENCES, LESSONS LEARNED

Event	Consequences		Lessons Learned
The fire grew rapidly, even if the trucks load was not considered as dangerous goods	- -	• Difficult to reach the fire because of smoke and heat • Tunnel users could not extinguish the fire with extinguisher	- HGV serious fires can happen even with "non dangerous" goods - Redefine the notion of "dangerous goods" for road tunnels
Fast and precise fire location detection	++	Optimization of the ventilation operation	Need of fire detection systems able to locate the fire rapidly
Fire detection system out of work	- -	Fire location unknown	Need of fire detection systems able to locate the fire rapidly
First alarm given by opacimeters	+	Fast alarm	Fire detection systems are to include smoke detection in addition to temperature detection
Two people died in a pressurized shelter because of heat	- -	2 victims	Pressurized shelters must be related to an evacuation route that is not the tunnel itself
First firemen arrived from the smokiest tunnel side	- -	Could not reach the fire	Need to inform the firemen on extended smoke plug in the tunnel
Misunderstanding about the fire site	- -	Arrived at the tunnel late	Need to train the firemen
Firemen entered the tunnel with inappropriate equipment	- -	Firemen were trapped in the tunnel. One died, and the evacuation of the others needed several hours	- Need to train the firemen - Cooperation needed between the tunnel operators and the firemen to inform them of the situation inside the tunnel
Some users rapidly decided to evacuate	++	Fewer victims	Need to inform the users on the behavior expected from them
Some users remained in their vehicles	- -	Victims died asphyxiated in the smoke	Need to inform the users on the behavior expected from them
Three users took refuge in an emergency call niche	-	• Perhaps they thought that they were in a safe area while it was not the case • Needed to be rescued by firemen	Emergency call niches have to be identified by the tunnel users as non-safe areas. There must be no confusion possible between emergency call niches and pressurized shelters or evacuation routes.
Car drivers entered the tunnel in spite of the red signal and siren	- -	• More victims	Need to inform the users on the behavior expected from them
Two separated control centers	- -	• Lack of coordination between the tunnel operators of the two centers complicated emergency ventilation operation	Only one control centre operating the tunnel
Fresh air supply at full capacity (from the bottom) .	- -	• Accelerated the smoke velocity toward the portals • Longer smoke plug	- Reduce fresh air supply if the longitudinal velocity is not controlled - Ventilation procedures have to be checked periodically in the light of available recommendations

TABLE G1
(*continued*)

Event	Consequences		Lessons learned
Fresh air supply from the ceiling stopped after the fire alarm	++	Permitted smoke stratification in the minutes following the fire	Fresh air supply must be reduced in the fire zone to favor the smoke stratification
Ventilation procedures were not followed (blowing instead of extraction)	-	• No smoke extraction in the fire zone • Blowing from the ceiling contributed to the smoke destratification	Need to train the tunnel operators to react to emergency situations
A vehicle queue build up at the backside of the fire	- -	• A high number of people in the dangerous zone • The fire transmitted to others vehicles	- Fire safety distance must be followed when vehicles have to stop in a tunnel. Need of information for the users. - Barriers are to be installed in long tunnels to avoid the accumulation of vehicles in dangerous zones
The tunnel was closed to the traffic rapidly (3 min after the fire beginning)	++	• Limited the number of people present in the tunnel	- Tunnel users have to be educated - Use physical barrier instead of traffic lights to close the tunnel
Operators could not know how many people were present in the tunnel at and after the fire beginning	-		- Count the entering and exiting vehicles

Ranking of event from very good (++) to very bad (- -).

crashed into an oncoming minibus carrying three people. The minibus caught fire immediately and then set the articulated truck and a following car on fire.

In the tunnel control room the computer-controlled fire program started immediately. Furthermore, the alarm was passed on to the local municipal police force and the rescue services in the town of Bregenz. From here, the fire department responsible for the southern portal was alarmed at 8:45 a.m. and at 8:47 a.m. the fire service responsible for the northern portal. At 8:48 a.m. control of operations at the southern portal was taken over by the fire department at the tunnel control centre.

While the alarms were being given, an explosive flare-up was observed on the monitors in the tunnel control centre. The scene of the accident was filled with smoke within seconds so that it was no longer possible to follow the course of the fire on the screens in the control centre.

The volunteer fire service of the town of Bregenz entered the tunnel at around 8:57 a.m. from both portals without having any exact information on the location of fire. Some minutes later four people fleeing in the direction of the southern cavern of the tunnel were rescued (the car driver causing the accident, the driver of the articulated truck involved in the accident and two truck drivers who had driven into the danger area from the southern side). These people and the rescue teams were caught up in the smoke which was drifting in a southerly direction.

From the scene of the accident the tunnel was completely filled with smoke in a northerly direction for approximately 270 m (885 ft) and in a southerly direction for approximately 800 m (2,625 ft). In spite of the excessive amount of smoke and the detonations which could be heard in the tunnel, four firemen attempted to reach the scene of the fire with a special fire engine equipped for tunnel use. This was intended to prevent any injured people who might be lying on the ground from being driven over in the dark by an emergency vehicle. The driver of the fire engine was only able to find his way in the tunnel by skirting the edge of the pavement with his tires in order not to lose his bearings.

As the visibility was zero because of the dense smoke, the firemen could not find the central line of the road even when they bent down or crawled along the ground. A fireman walking in front of the fire engine collided with a parked truck in the smoke because he was not able to see the obstacle in good time. Moreover, owing to the very poor visibility it was extremely difficult to drive the fire engine between the trucks and cars standing in the traffic jam in the tunnel.

In order to be able to finally begin extinguishing the fire, it was initially necessary in the smoke-filled tunnel for the firemen to identify by feeling around since they could not obtain visible information. They were able to feel a fire extinguishing bay from where they could open a water valve located in front of a hydrant. The extinguishing work was also greatly hindered by the heat at the scene of the fire. Nevertheless, the fire was under control approximately 1 hour after the fire departments had been alarmed.

Coordination of the fire-fighting measures was also greatly hindered by the fact that the two-way radio system in the tunnel stopped working. The three occupants of the minibus were burned to death in their vehicle. All other people (at the time of the accident there were approximately 60 people in vehicles in the tunnel) were able to escape from the tunnel unharmed.

The articulated truck, a car, and a minibus were destroyed by the fire. The tunnel ceiling at the scene of the fire showed spalling and cracks. Even the supporting consoles of the false ceiling on the internal vault were weakened by the heat of the fire. This structural damage stretched over a length of approximately 24 m (78.7 ft). Additionally, the tunnel was completely blackened by soot over a length of 35 m (114.8 ft) north of the scene of the accident, and 70 m (229.7 ft) in a southerly direction.

The operating equipment, such as the tunnel lighting, the aerial cables for the tunnel radio, and the supply lines in a cable duct on the tunnel ceiling, was damaged over a length of approximately 360 m (1,181 ft). In order that the tunnel could be put back into temporary operation, the false ceiling was initially supported with thick wooden poles and planks. In addition, a narrow-meshed steel net was fixed in place on the ceiling in the damaged part of the tunnel. After approximately 2 days it was possible to open the tunnel again for traffic. The final repair work was carried out in May 1995.

SUMMARY

1. Overtired drivers are a considerable danger to other road users.
2. The extinguishing work was hindered by smoke, heat, and the fact that the two-way radio connections did not work.
3. Dense smoke spread out over several hundred meters across the entire cross section of the tunnel.
4. Due to the dense smoke it was not possible to follow the course of the fire on the video monitoring system.

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation