NFPA®

502

Standard for Road Tunnels, Bridges, and Other Limited Access Highways

2020

NFPA®

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NFPA® 502

Standard for

Road Tunnels, Bridges, and Other Limited Access Highways

2020 Edition

This edition of NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*, was prepared by the Technical Committee on Road Tunnel and Highway Fire Protection and acted on by NFPA at its June Association Technical Meeting held June 17–20, 2019, in San Antonio, TX. It was issued by the Standards Council on August 5, 2019, with an effective date of August 25, 2019, and supersedes all previous editions.

This edition of NFPA 502 was approved as an American National Standard on August 25, 2019.

Origin and Development of NFPA 502

A tentative standard, NFPA 502T, *Standard for Limited Access Highways, Tunnels, Bridges, and Elevated Structures*, was prepared by the Technical Committee on Motor Vehicle Fire Protection and was adopted by the National Fire Protection Association on May 16, 1972, at its Annual Meeting in Philadelphia, PA. It was withdrawn in November 1975. In 1980, the committee rewrote the document as a recommended practice and included a chapter on air-right structures. It was adopted at the 1981 NFPA Annual Meeting.

Minor revisions to Chapters 2 through 5, primarily to water supply and fire apparatus requirements, were made in the 1987 edition.

The recommended practice was reconfirmed in 1992.

The 1996 edition incorporated a totally revised chapter on tunnels. Other revisions were made to correlate the new material in tunnel and air-right structure requirements with existing chapters and to update NFPA 502 with respect to current technology and practices.

The 1998 edition was developed by a task group appointed by the chairman of the Technical Committee on Motor Vehicle and Highway Fire Protection. With the planned revision from a recommended practice to a standard, the task group reviewed and completely revised all chapters of the document, with special emphasis on incorporating the lessons learned following completion of the full-scale fire ventilation test program at the Memorial Tunnel in West Virginia. Specific to the Memorial Tunnel Fire Ventilation Test Program, changes were made to Chapter 7, Tunnel Ventilation During Fire Emergencies. The title of the standard was also changed to reflect more accurately the contents and to properly identify the major focus of the standard. The previous title, *Recommended Practice on Fire Protection for Limited Access Highways, Tunnels, Bridges, Elevated Roadways, and Air-Right Structures*, was changed to *Standard for Road Tunnels, Bridges, and Other Limited Access Highways.*

The 2001 edition contained a significant editorial rewrite and reorganization of the document. Technical changes regarding emergency communication, emergency egress and lighting in tunnels, and tunnel ventilation were incorporated into the 2001 edition. Further changes were made to clarify the application of the standard based on tunnel length.

The 2004 edition included new requirements for the protection of concrete and steel tunnel structures, specific requirements for emergency lighting, and clarification of the travel distance to emergency exits in tunnels. The 2004 edition also updated the vehicle tunnel fire data in Annex A to more recent international research.

The 2008 edition added specific requirements for fire tests for tunnel structural elements and included revisions that further clarified the categorization of road tunnels; revisions regarding ventilation, tenable environment, and hazardous goods transport and a revision of the discussion topics in Annex E on fixed fire suppression systems.

The 2011 edition further developed performance-based design approaches for tunnels. Table 7.2 was updated to provide a more comprehensive review of the required systems for tunnels based on tunnel category. Chapter 9 was added to address the design of water-based fire-fighting systems. Additional changes to the document included the addition of system commissioning and periodic testing and updated annex material addressing design factors for life safety and property protection.

The 2014 edition included technical changes regarding emergency ventilation systems, electrical systems, emergency response, and emergency exits and new requirements for flammable and environmental hazards. Table 7.2, the comprehensive review of the required systems for tunnels based on category, was reorganized, updated, and moved to Annex A for ease of use. Additional changes to the document included clarifications for water-based fire-fighting and standpipe systems along with updated annex material corresponding to newly added requirements in the body of the standard.

The 2017 edition of NFPA 502 revised the list of considerations to be taken into account during an engineering analysis and added guidance in the annexes. Integrated testing on fire protection, life safety, and emergency systems, in accordance with NFPA 4, *Standard for Integrated Fire Protection and Life Safety System Testing*, is now required. Requirements for the structural protection of bridges were modified. New to Annex B was guidance on establishing noise levels in order to maintain a minimum level of speech intelligibility through the emergency communication system. The constant K_1 used in the critical velocity equation of Annex D was modified and is no longer a constant for heat release rates (HRR) less than or equal to 100 MW. In Annex E, information was provided regarding the effects of fire suppression on HRR and tunnel ventilation. A new Annex M was added providing guidance on the use of automatic fire detection systems in road tunnels.

The 2020 edition of NFPA 502 includes several revisions. In general requirements, a change was made to ensure that protection methods described assume a single fire event. Section 6.11 now requires an analysis to be performed on joints of nonconventional and nonrigid connections. Fixed water-based fire-fighting systems (FFFS) have been further explained throughout the code, as well as in several annex materials. Structural fire protection material has new requirements per 7.3.4. New references to *NFPA 72®, National Fire Alarm and Signaling Code®*, have been made in Chapter 7 for automatic fire detection systems. A section on Operations Control Centers (OCCs) has been updated in Chapter 13.

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Committee Scope: This Committee shall have primary responsibility for documents on fire prevention and fire protection measures to reduce loss of life and property damage for limited access highways, road tunnels, bridges, elevated highways, depressed highways, and roadways that are located beneath air-right structures. Excluded from this scope is the protection for facilities for the storage, repair, and parking of motor vehicles.

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2020 Edition

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NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Annex A.

A reference in brackets [ ] following a section or paragraph indicates material that has been extracted from another NFPA document. Extracted text may be edited for consistency and style and may include the revision of internal paragraph references and other references as appropriate. Requests for interpretations or revisions of extracted text shall be sent to the technical committee responsible for the source document.

Information on referenced and extracted publications can be found in Chapter 2 and Annex O.

Chapter 1 Administration

1.1 Scope.

1.1.1 This standard provides fire protection and fire-life safety requirements for limited access highways, road tunnels, bridges, elevated highways, depressed highways, and roadways that are located beneath air-right structures.

1.1.2 This standard establishes minimum requirements for each of the identified facilities.

1.1.3 This standard does not apply to the following structures:

(1) Parking garages
(2) Bus terminals
(3) Truck terminals
(4) Any other structure in which motor vehicles are stored, repaired, maintained, or parked

1.1.4 This standard shall be applicable where a structure or an element of a structure, including those specified in 1.1.3(1) through 1.1.3(4), is deemed to be a facility by the authority having jurisdiction (AHJ).

1.1.4.1 If any element of a structure cited in 1.1.3 is used to allow only the travel of road vehicles as a means of access to or egress from the structure, then it shall be characterized as a facility and treated as such under this standard.

1.2 Purpose. The purpose of this standard is to establish minimum criteria that provide protection from fire and its related hazards.

1.3 Application.

1.3.1* The provisions of this standard are the minimum necessary to provide protection from loss of life and property from fire.

1.3.2* The AHJ determines the application of this standard to facility alterations and fire protection system upgrades.

1.3.3 The portion of this standard that covers emergency procedures applies to both new and existing facilities.

1.4 Retroactivity. The provisions of this standard reflect a consensus of what is necessary to provide an acceptable degree of protection from the hazards addressed in this standard at the time the standard was issued.

1.4.1 Unless otherwise specified, the provisions of this standard shall not apply to facilities, equipment, structures, or installations that existed or were approved for construction or installation prior to the effective date of the standard. Where specified, the provisions of this standard shall be retroactive.

1.4.2 In those cases where the AHJ determines that the existing situation presents an unacceptable degree of risk, the AHJ shall be permitted to apply retroactively any portions of this standard deemed appropriate.

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

1.5 Equivalency. Nothing in this standard is intended to prevent the use of systems, methods, or devices of equivalent or superior quality, strength, fire resistance, effectiveness, durability, reliability, and safety over those prescribed by this standard, provided sufficient technical data demonstrates that the applied method, material, or device is equivalent to, or superior to, the requirements of this standard with respect to fire performance and safety.

1.5.1 Technical documentation shall be submitted to the AHJ to demonstrate equivalency.

1.5.2 The system, method, or device shall be approved for the intended purpose.

1.5.3 Alternative methods or devices approved as equivalent shall be recognized as being in compliance with this standard.

1.6 Units.

1.6.1* Metric units of measure in this standard are in accordance with the modernized metric system known as the International System of Units (SI). The liter unit (L), which is outside of but recognized by SI, is commonly used in the international fire protection industry. The appropriate units and conversion factors are specified in Table A.1.6.1.

1.6.2 If a value for measurement as provided in this standard is followed by an equivalent value in other units, the first stated value shall be regarded as the requirement. A given equivalent value can be an approximation.

Chapter 2 Referenced Publications

2.1 General. The documents or portions thereof listed in this chapter are referenced within this standard and shall be considered part of the requirements of this document.

2.2 NFPA Publications. National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169-7471.

NFPA 1, *Fire Code,* 2018 edition.

NFPA 3, *Standard for Commissioning of Fire Protection and Life Safety Systems,* 2018 edition.

NFPA 4, *Standard for Integrated Fire Protection and Life Safety System Testing,* 2018 edition.

NFPA 10, *Standard for Portable Fire Extinguishers,* 2018 edition.

NFPA 11, *Standard for Low-, Medium-, and High-Expansion Foam,* 2016 edition.

NFPA 13, *Standard for the Installation of Sprinkler Systems,* 2019 edition.

NFPA 14, *Standard for the Installation of Standpipe and Hose Systems,* 2019 edition.

NFPA 15, *Standard for Water Spray Fixed Systems for Fire Protection,* 2017 edition.

NFPA 16, *Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems,* 2019 edition.

NFPA 18, *Standard on Wetting Agents,* 2017 edition.

NFPA 18A, *Standard on Water Additives for Fire Control and Vapor Mitigation,* 2017 edition.

NFPA 20, *Standard for the Installation of Stationary Pumps for Fire Protection,* 2019 edition.

NFPA 22, *Standard for Water Tanks for Private Fire Protection,* 2018 edition.

NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances,* 2019 edition.

NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems,* 2020 edition.

NFPA 70®, National Electrical Code®, 2020 edition.

NFPA 72®, National Fire Alarm and Signaling Code, 2019 edition.

NFPA 80, *Standard for Fire Doors and Other Opening Protectives,* 2019 edition.

NFPA 92, *Standard for Smoke Control Systems,* 2018 edition.

NFPA *101®, Life Safety Code®,* 2018 edition.

NFPA 110, *Standard for Emergency and Standby Power Systems,* 2019 edition.

NFPA 111, *Standard on Stored Electrical Energy Emergency and Standby Power Systems,* 2019 edition.

NFPA 241, *Standard for Safeguarding Construction, Alteration, and Demolition Operations,* 2018 edition.

NFPA 262, *Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces,* 2019 edition.

NFPA 750, *Standard on Water Mist Fire Protection Systems,* 2019 edition.

NFPA 820, *Standard for Fire Protection in Wastewater Treatment and Collection Facilities,* 2020 edition.

NFPA 1561, *Standard on Emergency Services Incident Management System and Command Safety,* 2014 edition.

NFPA 1670, *Standard on Operations and Training for Technical Search and Rescue Incidents,* 2017 edition.

NFPA 1963, *Standard for Fire Hose Connections,* 2019 edition.

2.3 Other Publications.

2.3.1 ASTM Publications. ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959.

ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials*, 2018a.

ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*, 2018a.

ASTM E136, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C*, 2016a.

ASTM E2652, *Standard Test Method for Behavior of Materials in a Tube Furnace with a Cone-shaped Airflow Stabilizer, at 750°C*, 2016.

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2.3.2 CSA Publications. Canadian Standards Association, 178 Rexdale Boulevard, Toronto, Ontario, Canada M9W 1R3.

CSA C22.2 No. 0.3, *Test Methods for Electrical Wires and Cables*, 2009, reaffirmed 2014.

2.3.3 Efectis Publications. Efectis Nederland, Brandpuntlaan Zuid 16, 2665 NZ, Bleiswijk, The Netherlands, www.efectis.com.

2008-Efectis-R0695, "Fire Testing Procedure for Concrete Tunnel Linings," 2008.

2.3.4 FHWA Publications. Federal Highway Administration, 1200 New Jersey Avenue, SE, Washington, DC 20590.

Manual on Uniform Traffic Control Devices (MUTCD), 2012.

2.3.5 IEEE Publications. IEEE, Three Park Avenue, 17th Floor, New York, NY 10016-5997.

FT4/IEEE 1202, *Standard for Flame-Propagation Testing of Wire and Cable*, 2006.

2.3.6 ISO Publications. International Organization for Standardization, Central Secretariat, BIBC II, 8, Chemin de Blandonnet, CP 401, 1214 Vernier, Geneva, Switzerland.

ISO 1182, *Reaction to fire tests for products — Non-combustibility test*, 2010.

2.3.7 Military Specifications. Department of Defense Single Stock Point, Document Automation and Production Service, Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

MIL-DTL-24643C, *Detail Specification: Cables, Electric, Low Smoke Halogen-Free, for Shipboard Use*, Revision C.

2.3.8 OSHA Publications. Occupational Safety and Health Administration, 200 Constitution Avenue, NW, Washington, DC 20210.

Title 29, Code of Federal Regulations, Part 1910.146, "Permit-Required Confined Spaces."

Δ **2.3.9 UL Publications.** Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096.

ANSI/UL 1685, *Vertical-Tray Fire-Propagation and Smoke-Release Test for Electrical and Optical-Fiber Cables*, 2015.

UL 1724, *Outline of Investigation for Fire Tests for Electrical Circuit Protective Systems*, 2006.

ANSI/UL 2196, *Standard for Fire Test for Circuit Integrity of Fire-Resistive Power, Instrumentation, Control, and Data Cables*, 2017.

2.3.10 Other Publications.

Merriam-Webster's Collegiate Dictionary, 11th edition, Merriam-Webster, Inc., Springfield, MA, 2003.

EN 13501-1, *Fire classification of construction products and building elements — Part 1: Classification using data from reaction to fire tests*, 2007 + A1:2010.

2.4 References for Extracts in Mandatory Sections.

NFPA 3, *Recommended Practice for Commissioning of Fire Protection and Life Safety Systems,* 2018 edition.

NFPA 10, *Standard for Portable Fire Extinguishers,* 2018 edition.

NFPA 70®, *National Electrical Code*®, 2020 edition.

NFPA *101*®, *Life Safety Code*®, 2018 edition.

NFPA 402, *Guide for Aircraft Rescue and Fire-Fighting Operations,* 2019 edition.

NFPA 472, *Standard for Competence of Responders to Hazardous Materials/Weapons of Mass Destruction Incidents,* 2018 edition.

NFPA 921, *Guide for Fire and Explosion Investigations,* 2017 edition.

NFPA 1142, *Standard on Water Supplies for Suburban and Rural Fire Fighting,* 2017 edition.

NFPA 1901, *Standard for Automotive Fire Apparatus,* 2016 edition.

NFPA 5000®, *Building Construction and Safety Code*®*,* 2018 edition.

Chapter 3 Definitions

3.1 General. The definitions contained in this chapter shall apply to the terms used in this standard. Where terms are not defined in this chapter or within another chapter, they shall be defined using their ordinarily accepted meanings within the context in which they are used. *Merriam-Webster's Collegiate Dictionary*, 11th edition, shall be the source for the ordinarily accepted meaning.

3.2 NFPA Official Definitions.

3.2.1* Approved. Acceptable to the authority having jurisdiction.

3.2.2* Authority Having Jurisdiction (AHJ). An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

3.2.3 Labeled. Equipment or materials to which has been attached a label, symbol, or other identifying mark of an organization that is acceptable to the authority having jurisdiction and concerned with product evaluation, that maintains periodic inspection of production of labeled equipment or materials, and by whose labeling the manufacturer indicates compliance with appropriate standards or performance in a specified manner.

3.2.4* Listed. Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of products or services, that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services, and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose.

3.2.5 Shall. Indicates a mandatory requirement.

3.2.6 Should. Indicates a recommendation or that which is advised but not required.

3.2.7 Standard. An NFPA Standard, the main text of which contains only mandatory provisions using the word "shall" to indicate requirements and that is in a form generally suitable for mandatory reference by another standard or code or for adoption into law. Nonmandatory provisions are not to be considered a part of the requirements of a standard and shall be located in an appendix, annex, footnote, informational note, or other means as permitted in the NFPA Manuals of Style. When used in a generic sense, such as in the phrase "standards development process" or "standards development activities," the term "standards" includes all NFPA Standards, including Codes, Standards, Recommended Practices, and Guides.

3.3 General Definitions.

3.3.1 Agency. The organization legally established and authorized to operate a facility.

3.3.2 Alteration. For limited access highways, road tunnels, bridges, elevated highways, depressed highways, and roadways that are located beneath air-right structures, a modification, replacement, or other physical change to an existing facility.

3.3.3 Alternative Fuel. A motor vehicle fuel other than gasoline and diesel.

3.3.4 Ancillary Facility. A structure, space, or area that supports the operation of limited access highways, road tunnels, bridges, elevated highways, depressed highways, and roadways that are under air-right structures, that are usually used to house or contain operating, maintenance, or support equipment and functions.

3.3.5* Backlayering. The movement of smoke and hot gases counter to the direction of the ventilation airflow.

3.3.6* Basis of Design (BOD). A document that describes the concepts and decisions used to meet the owner's project requirements and governing laws, regulations, codes, and standards. [**3**, 2018]

3.3.7 Bridge. A structure spanning and providing a highway across an obstacle such as a waterway, railroad, or another highway.

3.3.8* Building. Any structure used or intended for supporting or sheltering any use or occupancy.

3.3.9 Cable Tray System. A unit or assembly of units or sections and associated fittings forming a structural system used to securely fasten or support cables and raceways. [**70:**392.2]

3.3.10 Combustible. Capable of undergoing combustion.

3.3.11 Command Post (CP). The location at the scene of an emergency where the incident commander is located and where command, coordination, control, and communications are centralized. [**402,** 2019]

3.3.12 Commissioning. A systematic process that provides documented confirmation that specific and interconnected fire protection, life safety, and emergency systems function according to the intended design criteria set forth in the project documents and satisfy the owner's operational needs, including compliance requirements of any laws, regulations, codes, and standards requiring fire protection, life safety, and emergency systems.

3.3.13 Congestion. A traffic condition characterized by slow speeds or stopped traffic that occurs when volume increases or an incident occurs that impedes traffic flow.

3.3.14 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.

3.3.15 Decibel. The logarithmic units associated with sound pressure level.

3.3.15.1 ***A-weighted Decibel (dBA).*** Decibel values with weighting applied over the frequency range of 20 Hz to 20 kHz to reflect human hearing.

3.3.15.2 ***Un-weighted Decibel (dBZ).*** Decibel values without weighting applied.

N **3.3.16 Degraded Modes of Operation.** Any condition in which fire protection and life safety systems and other related systems are not operating at normal capacity.

3.3.17 Deluge System. An open fixed water-based fire suppression system activated either manually or automatically.

N **3.3.18* Design Fire Scenario.** A set of conditions that defines the fire development.

3.3.19 Dry Standpipe. A standpipe system designed to have piping contain water only when the system is being utilized.

3.3.20 Dynamic Vehicle Envelope. The space within the tunnel roadway that is allocated for maximum vehicle movement.

3.3.21* Emergency Communications. Radio and telephone systems located throughout the facility dedicated to provide the ability for direct communications during an emergency.

3.3.22 Emergency Exits. Doors, egress stairs, or egress corridors leading to a point of safety, such as cross-passages leading to an adjacent nonincident tunnel and portals.

3.3.23 Emergency Response Plan. A plan developed by an agency, with the cooperation of all participating agencies, that details specific actions to be performed by all personnel who are expected to respond during an emergency.

3.3.24 Engineering Analysis. An analysis that evaluates all factors that affect the fire safety of a facility or a component of a facility.

3.3.25 Equivalency. An alternative means of providing an equal or greater level of safety than that afforded by strict conformance to prescribed codes and standards.

3.3.26 Facility. A limited access highway, road tunnel, roadway beneath an air-right structure, bridge, or elevated highway.

Δ **3.3.27 Fire Apparatus.** A vehicle designed to be used under emergency conditions to transport personnel and equipment to support the suppression of fires or mitigation of other hazardous situations. [**1901,** 2016]

3.3.28 Fire Department Connection. A connection through which the fire department can pump supplemental water into the fixed water-based fire-fighting system, sprinkler system, standpipe system, or other systems furnishing water for fire suppression and extinguishment to supplement existing water supplies.

Δ **3.3.29 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 mitigate the condition or situation.

Δ **3.3.30* Fire Growth Rate.** Rate of change of the fire's heat release.

N **3.3.31* Fire Risk Assessment.** A process to characterize the risk associated with fire, which addresses the design fire scenario or scenarios of concern, their probability, and their potential consequences.

N **3.3.31.1** ***Risk Acceptance Criteria.*** The units and threshold values against which a fire risk assessment is judged.

3.3.32 Fire Suppression. The sharp reduction of the rate of heat release of a fire and the prevention of regrowth.

Δ **3.3.33* Fixed Water-Based Fire-Fighting System (FFFS).** A system permanently attached to the tunnel that is able to spread a water-based extinguishing agent in all or part of the tunnel.

Δ **3.3.34* Heat Release Rate (HRR).** The rate at which heat energy is generated by burning. [**921,** 2017]

3.3.35 Highway. Any paved facility on which motor vehicles travel.

3.3.35.1* ***Depressed Highway.*** An uncovered, below-grade highway or boat section where walls rise to the grade surface and where emergency response access is usually limited.

3.3.35.2 ***Elevated Highway.*** A highway that is constructed on a structure that is above the surface but that does not cross over an obstacle as in the case of a bridge.

3.3.35.3 ***Limited Access Highway.*** A highway where preference is given to through-traffic by providing access connections that use only selected public roads and by prohibiting crossings at grade and at direct private driveways.

3.3.36 Hose Connection. A combination of equipment provided for the connection of a hose to a standpipe system that includes a hose valve with a threaded outlet.

3.3.37 Hose Valve. The valve to an individual hose connection.

3.3.38* Incident Commander (IC). The individual responsible for all incident activities, including the development of strategies and tactics and the ordering and the release of resources. [**472,** 2018]

3.3.39* Length of Bridge or Elevated Highway. The linear distance measured along the centerline of a bridge or elevated highway structure from abutment to abutment.

3.3.40 Length of Tunnel. The length from face of portal to face of portal that is measured using the centerline alignment along the tunnel roadway.

3.3.41 Level Equivalent (L_{eq}). The average sound level over time on an acoustical energy basis.

3.3.42 Mandatory Requirement. A requirement prefaced by the word “shall” within the standard.

3.3.42.1 ***Conditionally Mandatory Requirement.*** A requirement that is based on the results of an engineering analysis.

3.3.42.2 ***Nonmandatory Requirement.*** A requirement that is not prefaced by the word “shall” and most likely contained in an annex, a footnote, or Informational Note of the standard.

3.3.43 Motorist. A vehicle occupant, including the driver and passenger(s).

3.3.44* Noncombustible Material. See Section 4.8.

3.3.45 Operations Control Center. A dedicated location that controls and coordinates the facility operations and from which communication is maintained with the agency’s supervisory and operating personnel and with participating agencies where required.

3.3.46 Participating Agency. A public, quasi-public, or private agency that has agreed to cooperate with and assist the authority during an emergency.

3.3.47* Point of Safety. For road tunnels, bridges, and limited access highways, 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.

3.3.48 Portable Fire Extinguisher. A portable device, carried or on wheels and operated by hand, containing an extinguishing agent that can be expelled under pressure for the purpose of suppressing or extinguishing fire. [**10,** 2018]

3.3.49 Portal. The interface between a tunnel and the atmosphere through which vehicles pass; a connection point to an adjacent structure.

3.3.50 Primary Structural Element. An element of the structure whose failure is expected to result in the collapse of the structure or the inability of the structure to perform its function.

3.3.51 Progressive Structural Collapse. The spread of an initial local failure from element to element resulting in the eventual collapse of an entire structure or a disproportionately large part of it.

Δ **3.3.52 Raceway.** An enclosed channel of metal or nonmetallic materials designed expressly for holding wires, cables, or busbars, with additional functions as permitted in *NFPA 70*. Raceways include, but are not limited to, rigid metal conduit, rigid nonmetallic conduit, intermediate metal conduit, liquidtight flexible conduit, flexible metallic tubing, flexible metal conduit, electrical nonmetallic tubing, electrical metallic tubing, underfloor raceways, cellular concrete floor raceways, cellular metal floor raceways, surface raceways, wireways, and busways.

3.3.53 Road Tunnel. An enclosed roadway for motor vehicle traffic with vehicle access that is limited to portals.

3.3.54 Roadway. The volume of space that is located above the pavement surface through which motor vehicles travel.

3.3.55 Rural. Those areas that are not unsettled wilderness or uninhabitable territory but are sparsely populated with densities below 500 persons per square mile. [**1142,** 2017]

3.3.56 RWS (Rijkswaterstaat) Time-Temperature Curve. The fire test and time-temperature curve described in the report, Efectis-R0695, 2008.

3.3.57 Self-Rescue. People leaving the hazardous area or dangerous situation without any professional (fire fighters, rescue personnel, etc.) help.

3.3.58 Smoke Release Rate. The rate at which smoke is generated by burning.

3.3.59 Sound Pressure Level. The logarithmic ratio of the root-mean squared sound pressure to the reference sound pressure (2.0×10^{-5} Pascals).

3.3.60 Structure. That which is built or constructed and limited to buildings and non-building structures as defined herein. [**5000,** 2018]

3.3.60.1* ***Air-Right Structure.*** A structure other than a skywalk bridge that is built over a roadway using the roadway’s air rights. [**5000,** 2018]

3.3.61 Tenable Environment. An environment that permits evacuation or rescue, or both, of occupants for a specific period of time.

N **3.3.62 Wayfinding.** The use of specific means to enhance the identification of the escape path to assist in evacuation.

Chapter 4 General Requirements

Δ **4.1* Level of Fire Protection.** The level of fire protection necessary for the facility shall be achieved by implementing the requirements of this standard for each subsystem and integrating the use of these systems, features, and materials.

N **4.1.1** The protection methods described in this standard shall assume a single fire event.

4.2 Safeguards During Construction. During the course of construction, repair, alteration, or demolition of any facility addressed in this standard, the provisions of NFPA 241 shall apply.

4.2.1 Standpipe Installations in Tunnels Under Construction.

4.2.1.1* Where required by the authority having jurisdiction (AHJ), a standpipe system shall be installed, tested, and maintained in tunnels under construction in accordance with NFPA 241, NFPA 14, and NFPA 25.

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Δ **4.3 Fire Protection and Fire-Life Safety Factors.** The requirements for ensuring human safety during the evacuation and rescue phases are substantially different from the requirements to protect the structural components of the facility, and shall be separately defined.

4.3.1* Regardless of the length of the facility, at a minimum, the following factors shall be considered as part of a holistic multidisciplinary engineering analysis of the fire protection and life safety requirements for the facilities covered by this standard:

(1) New facility or alteration of a facility
(2) Transportation modes using the facility
(3) Anticipated traffic mix and volume
(4) Restricted vehicle access and egress
(5) Fire emergencies ranging from minor incidents to major catastrophes
(6) Potential fire emergencies including but not limited to the following:
    (a) At one or more locations inside or on the facility
    (b) In close proximity to the facility
    (c) At facilities a long distance from emergency response facilities
(7) Exposure of emergency systems and structures to elevated temperatures
(8) Traffic congestion and control requirements during emergencies
(9) Fire protection features, including but not limited to the following:
    (a) Fire alarm and detection systems
    (b) Standpipe systems
    (c) Water-based fire-fighting systems
    (d) Ventilation systems
    (e) Emergency communications systems
    (f) Protection of structural elements
(10) Facility components, including emergency systems
(11) Evacuation and rescue requirements
(12) Emergency response time
(13) Emergency vehicle access points
(14) Emergency communications to appropriate agencies
(15) Facility location such as urban or rural (risk level and response capacity)
(16) Physical dimensions, number of traffic lanes, and roadway geometry
(17) Natural factors, including prevailing wind and pressure conditions
(18) Anticipated cargo
(19) Impact to buildings or landmarks near the facility
(20) Impacts to facility from external conditions and/or incidents
(21) Traffic operating mode (unidirectional, bidirectional, switchable, or reversible)

4.3.2* Fire Protection, Life Safety, and Emergency Systems Reliability. Regardless of the length or type of facility, the intended function of the fire protection, life safety, or emergency systems that address an emergency shall not be subject to failure as a result of the emergency that those systems are designed to address when working in combination.

4.3.3* Limited Access Highways. Fire protection for limited access highways shall comply with the requirements of Chapter 5.

4.3.4 Bridges and Elevated Highways. Fire protection for bridges and elevated highways shall comply with the requirements of Chapter 6.

4.3.5* Depressed Highways. Standpipe systems or fire extinguishers, or both, shall be installed on depressed highways where physical factors prevent or impede access to an acceptable water supply.

4.3.6* Road Tunnels. Fire protection for road tunnels shall comply with the requirements of Chapter 7.

4.3.7* Roadway Beneath Air-Right Structures. Fire protection for roadways that are located beneath air-right structures shall comply with the requirements of Chapter 8.

4.3.8* Ancillary Facilities. All related ancillary facilities that support the operation of limited access highways, depressed highways, bridges and elevated highways, and road tunnels shall be protected as required by all applicable NFPA standards and applicable building codes except as modified in this standard.

Δ **4.4 Emergency Response Plan.**

4.4.1* Emergency traffic-control procedures shall be established to regulate traffic during an emergency.

4.4.1.1 Traffic shall be managed to avoid blocking access to emergency responders or otherwise interfering with the mitigation of the fire or emergency event. Traffic incident management shall be in conformance with Chapter 6I, "Control of Traffic Through Traffic Incident Management Areas," of the *Manual on Uniform Traffic Control Devices (MUTCD).*

4.4.2 Emergency procedures and the development of an emergency response plan for the facilities covered by this standard shall be completed in accordance with the requirements of Chapter 13.

4.5 Emergency Communications. Emergency communications, where required by the AHJ, shall be provided by the installation of outdoor-type telephone boxes, coded alarm telegraph stations, radio transmitters, or other approved devices that meet the following requirements:

(1) They shall be made conspicuous by means of indicating lights or other approved methods.
(2) They shall be identified by a readily visible number plate or other approved device.
(3) They shall be posted with instructions for use by motorists.
(4) They shall be located in approved locations so that motorists can park vehicles clear of the travel lanes.
(5) Emergency communication devices shall be protected from physical damage from vehicle impact.
(6) Emergency communication devices shall be connected to an approved constantly attended location.

4.6 Signage. Signs, mile markers, or other approved location reference markers shall be installed to provide a means for determining the relative location within or along the facility.

4.7 Commissioning and Integrated Testing.

4.7.1 The agency shall require the development of a commissioning plan and conduct integrated testing to facilitate the verification of the operational readiness of all installed fire protection, life safety, and emergency systems required by this standard, other applicable NFPA standards, and as required within the basis of design (BOD) for construction.

4.7.2 The commissioning plan shall be reviewed and approved by the AHJ where required.

N **4.7.3** Requirements, procedures, and documentation for commissioning shall be in accordance with NFPA 3 and this standard.

4.7.4 Integrated system testing shall be performed on fire protection, life safety, and emergency systems.

4.7.4.1 This testing shall confirm that the operation, interaction, and coordination of multiple individual systems perform their intended function.

4.7.4.2 Requirements, procedures, and documentation shall be in accordance with NFPA 4 and as required by this standard.

4.7.4.3 Results reported shall verify that the systems required to operate together as a whole achieve the overall fire protection and life safety objectives.

4.8* Noncombustible Material. A material that complies with any one of the following shall be considered a noncombustible material:

(1)* The material, in the form in which it is used and under the conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors, when subjected to fire or heat.
(2) The material is reported as passing ASTM E136, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C*.
(3) The material is reported as complying with the pass/fail criteria of ASTM E136 when tested in accordance with the test method and procedure in ASTM E2652, *Standard Test Method for Behavior of Materials in a Tube Furnace with a Cone-shaped Airflow Stabilizer, at 750°C*.
(4) The material is reported as complying with the pass/fail criteria of EN 13501-1, *Fire classification of construction products and building elements — Part 1: Classification using data from reaction to fire test*, in relation to ISO 1182, *Reaction to fire tests for products — Non-combustibility test*.

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4.9 Structural Anchorage.

4.9.1 Attachments to the structure that penetrate a passive fire protection system shall not adversely affect the thermal performance of the system.

4.9.2 Passive fire protection systems shall not adversely affect the integrity of attachments to the structure.

Chapter 5 Limited Access Highways

5.1 General. This chapter shall provide fire protection requirements for limited access highways.

5.2 Traffic Control.

5.2.1 Traffic control devices or other approved methods shall be provided at the points of entry to a limited access highway to allow fire apparatus and other emergency responders to enter unimpeded.

5.3* Fire Apparatus.

5.3.1 Where limited accessibility to a highway or section thereof might prevent or delay an approved emergency response time, emergency response plans shall identify mitigating measures for various levels of emergency.

5.3.2 Where a dedicated means of access for use by emergency responders to enter the facility is provided, procedures for using such access shall be included in the emergency response plan.

5.4 Protection of Structural Elements.

5.4.1 Acceptable means shall be included within the design of the limited access highway to protect structures in accordance with this standard to achieve the following:

(1) Support fire fighter accessibility
(2) Mitigate structural damage from fire to prevent progressive structural collapse
(3) Minimize economic impact

5.4.2 Critical structural members shall be protected from collision and high-temperature exposure that can result in dangerous weakening or complete collapse.

5.5* Incident Detection. (Reserved)

5.6* Fire Hydrants. (Reserved)

5.7 Drainage. On limited access highways, drainage systems to channel and collect surface runoff, which can include spilled hazardous or flammable liquids, shall be designed to direct to areas that do not introduce additional fire hazards on or outside the facility.

Chapter 6 Bridges and Elevated Highways

6.1* General.

6.1.1 This chapter shall provide fire protection requirements for bridges and elevated highways.

6.1.2 Bridges or elevated highways and spaces below bridges and elevated highways that are fully enclosed and meet the definition of a tunnel and the tunnel length requirements of Section 7.2 shall meet the requirements of Chapter 7.

6.2* Application. For the purpose of this standard, length or other elements of engineering analysis of the bridge or elevated highway shall dictate the minimum fire protection requirements.

6.2.1 For bridges or elevated highways less than 300 m (1000 ft) in length, the provisions of this chapter shall not apply.

6.2.2* Where a bridge or elevated highway does not fully enclose the roadway on both sides, the decision to consider it as a road tunnel shall be made by the authority having jurisdiction (AHJ) after an engineering analysis in accordance with 4.3.1.

6.2.3 In rural areas, Sections 6.4 and 6.7 of this standard shall not apply.

6.3 Protection of Structural Elements.

6.3.1* Acceptable means shall be included within the design of the bridge or elevated highway to prevent progressive structural collapse or collapse of primary structural elements.

6.3.1.1 Primary structural elements shall be protected in accordance with this standard in order to achieve the following functional requirements:

(1) Support fire fighter accessibility
(2) Minimize economic impact
(3) Mitigate structural damage

6.3.2* Where it has been determined by engineering analysis that collapse of the bridge or elevated highway will impact life safety or have unacceptable implications, the bridge or elevated highway, including its primary structural elements, shall be protected from collision and capable of withstanding the time-temperature exposure represented by the selected design fire scenario.

6.3.2.1 The design fire scenario shall be used to design a bridge or elevated highway.

6.3.2.2 The selection of the design fire scenario shall consider the types of vehicles passing under and on the bridge or elevated highway.

6.3.3 For through truss bridges, suspension (including cable stay) bridges, or elevated highways, an engineering analysis shall be prepared to determine acceptable risk due to fire, including possible collapse scenarios.

6.4 Incident Detection.

6.4.1 Manual Fire Alarm Boxes.

6.4.1.1 Where the length of a bridge or elevated highway exceeds 3.2 km (2 miles), a manual fire alarm box shall be mounted in a NEMA Enclosure Type 4X or equivalent box at intervals of not more than 1.0 km (0.6 mile).

6.4.1.2 The location of the manual fire alarm boxes shall be approved by the AHJ.

6.4.1.3 The alarm shall indicate the location of the manual fire alarm box at the monitoring station.

6.4.1.4 The system shall be installed, inspected, and maintained in compliance with *NFPA 72*.

6.4.2 Closed-Circuit Television (CCTV) Systems.

6.4.2.1 Where the length of a bridge or elevated highway exceeds 300 m (1000 ft), a CCTV system shall be installed on the bridge.

6.4.2.2 The CCTV system shall be capable of viewing the entire length of the bridge or elevated highway from a single monitoring station using multiple cameras and camera locations.

6.5 Traffic Control. The decision to require a means to stop traffic from entering a bridge shall be made by the AHJ after an engineering analysis in accordance with 4.3.1.

6.6 Standpipe, Fire Hydrants, and Water Supply.

6.6.1* Applicability. Where the length of a bridge or elevated highway exceeds 300 m (1000 ft), a horizontal standpipe system shall be installed on the structure in accordance with the requirements of Chapter 10.

6.6.2 Where the transverse width of a bridge or elevated highway exceeds 30 m (100 ft), or the travel direction lanes are physically separated by a barrier, and the structure meets the requirements of 6.6.1 above, the standpipe system shall be installed on each side of the bridge or elevated highway.

6.6.3* Fire Hydrants (Reserved).

6.7 Portable Fire Extinguishers.

6.7.1 Where the length of a bridge or elevated highway exceeds 3.2 km (2 miles), a portable fire extinguisher, with a rating of 2-A:20-B:C mounted in an NFPA 10–compliant cabinet, shall be installed at intervals of not more than 1.0 km (0.6 mile). No portable extinguisher shall be placed within 0.6 km (0.4 mile) of the end of the bridge or elevated highway.

6.7.2 To facilitate safe use by the public, the maximum weight of each extinguisher shall be 9 kg (20 lb).

6.7.3 Portable fire extinguishers shall be selected, installed, inspected, and maintained in accordance with NFPA 10.

6.7.4 The location of the portable fire extinguishers shall be approved by the AHJ.

6.8 Drainage.

6.8.1 On bridges and elevated highways, drainage systems to channel and collect surface runoff, which can include spilled hazardous or flammable liquids, shall be designed to drain to areas that do not introduce additional fire hazards on or outside the facility.

6.8.2 Expansion joints shall be designed to prevent spillage to the area below the bridge or elevated highway.

6.8.3 Bridges or elevated highways with combustible expansion joint or bearing system material, vulnerable to a spill of flammable liquids, shall have a roadway surface drainage system capable of intercepting a spill.

6.9 Hazardous Locations. Confined spaces meeting the definition of NFPA 1670 shall be labeled in accordance with 29 CFR 1910.146.

6.10 Control of Hazardous Materials. Control of hazardous materials shall be in accordance with the requirements of Chapter 14.

N **6.11 Joints Between Structural Elements.** An analysis shall be performed on joints of nonconventional and nonrigid connections.

Chapter 7 Road Tunnels

7.1* General.

7.1.1* This chapter shall provide fire protection and life safety requirements for road tunnels.

7.1.2* For road tunnels that include either passive fire protection or fixed water-based fire-fighting systems (FFFS), or both, the impact of these systems during a fire on protection of structural elements, the tenable environment within the tunnel, and the tunnel ventilation system shall be evaluated.

7.2* Application. For the purpose of this standard, factors described in 4.3.1 shall dictate fire protection and fire-life safety requirements. The minimum fire protection and fire-life safety requirements, based on tunnel length, are categorized as follows:

(1) Category X — Where tunnel length is less than 90 m (300 ft), an engineering analysis shall be performed in accordance with 4.3.1, an evaluation of the protection of structural elements shall be conducted in accordance with Section 7.3, and traffic control systems shall be installed in accordance with the requirements of Section 7.6.
(2) Category A — Where tunnel length is 90 m (300 ft) or greater, an engineering analysis shall be performed in accordance with 4.3.1, an evaluation of the protection of structural elements shall be conducted in accordance with Section 7.3, and a standpipe system and traffic control systems shall be installed in accordance with the requirements of Chapter 10 and Section 7.6.
(3) Category B — Where tunnel length equals or exceeds 240 m (800 ft) and where the maximum distance from any point within the tunnel to a point of safety exceeds 120 m (400 ft), all provisions of this standard shall apply unless noted otherwise in this document.
(4) Category C — Where the tunnel length equals or exceeds 300 m (1000 ft), all provisions of this standard shall apply unless noted otherwise in this document.
(5) Category D — Where the tunnel length equals or exceeds 1000 m (3280 ft), all provisions of this standard shall apply.

7.2.1* Where a roadway or portion of a roadway is not fully enclosed on both sides, is not fully enclosed on top, or any combination thereof, the decision by the authority having jurisdiction (AHJ) to consider the roadway as a road tunnel shall be made after an engineering analysis is performed in accordance with 4.3.1.

7.3 Protection of Structural Elements.

7.3.1* For all tunnel categories, acceptable means shall be included within the design of the tunnel to prevent progressive collapse of primary structural elements and to prevent the failure of support for overhead equipment and systems in accordance with this standard to achieve the following functional requirements in addition to life safety:

(1) Support fire fighter accessibility
(2) Minimize economic impact
(3) Mitigate structural damage

7.3.2* The structure shall be capable of withstanding the temperature exposure represented by the Rijkswaterstaat (RWS) time-temperature curve or other recognized standard time-temperature curve that is acceptable to the AHJ, following an engineering analysis as required in Chapter 4.

7.3.3 During a 120-minute period of fire exposure or other time that is acceptable to the AHJ, the following failure criteria shall be satisfied:

(1) Regardless of the material the primary structural element is made of, irreversible damage and deformation leading to progressive structural collapse shall be prevented.
(2)* Tunnels with concrete structural elements shall be designed such that fire-induced spalling, which leads to progressive structural collapse, is prevented.

Δ **7.3.4** Structural fire protection material, where provided, shall satisfy the following performance criteria:

(1) Tunnel structural elements shall be protected to achieve the following for concrete:
    (a) The concrete is protected such that fire-induced spalling is prevented.
    (b) The temperature of the concrete surface does not exceed 380°C (716°F).
    (c) The temperature of the steel reinforcement within the concrete [assuming a minimum cover of 25 mm (1 in.)] does not exceed 250°C (482°F).
(2) Tunnel structural elements shall be protected to achieve a lining temperature not exceeding 300°C (572°F) for steel or cast iron.
(3) The material shall be noncombustible in accordance with Section 4.8.
(4) The material shall have a minimum melting temperature of 1350ºC (2462ºF).
(5) The material shall meet the fire protection requirements with less than 5 percent moisture content by weight and when fully saturated with water, in accordance with the approved time-temperature curve.

N **7.3.5 Joints Between Structural Elements.** An analysis shall be performed on joints of nonconventional and nonrigid connections.

N **7.3.6** All fasteners, intermediate support elements, and anchors that attach equipment and devices not otherwise addressed in other codes and standards to the structure above roadway and walkway surfaces shall be capable of maintaining support during exposure to a minimum of 450°C (842°F) for a minimum of 120 minutes.

7.4 Fire Alarm and Detection.

Δ **7.4.1** Tunnels described in categories B, C, and D shall have at least two independent means of identifying and locating a fire.

Δ **7.4.2** Tunnels described in categories B, C, and D shall have an automatic fire detection system in accordance with 7.4.6.

7.4.3* Closed-circuit television (CCTV) systems with traffic-flow indication devices or surveillance cameras shall be permitted for use to identify and locate fires in tunnels with 24-hour supervision.

7.4.4 When water-based fire-fighting systems are installed in road tunnels, an automatic fire detection system shall be provided in accordance with 7.4.6.

7.4.5 Ancillary spaces within tunnels defined in categories B, C, and D (such as pump stations and utility rooms) and other areas shall be supervised by automatic fire alarm systems in accordance with 7.4.6.

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7.4.6* Automatic Fire Detection Systems.

7.4.6.1* Automatic fire detection systems shall be installed in accordance with Chapter 17 of *NFPA 72*, or other equivalent international standards, and approved by the AHJ (*see also Annex M*).

7.4.6.2* Where a fire detection system is installed in accordance with the requirements of 7.4.6.1, signals for the purpose of automatically indicating the direction of evacuation and relocation of occupants shall not be required.

7.4.6.3 The performance of automatic fire detection systems shall include details of the fire signature required to initiate the alarm.

7.4.6.4 Automatic fire detection systems shall be capable of identifying the location of the fire within 15 m (50 ft).

7.4.6.5 Spot detectors shall have a light that remains on until the device is reset.

7.4.6.6 Automatic fire detection systems within a tunnel shall be zoned to correspond with the tunnel ventilation zones and FFFS where either, or both, of these systems are provided.

7.4.6.7* Automatic fire detection systems shall be able to provide detection in the early stages of a developing fire within the tunnel under anticipated air velocity.

7.4.7* Fire Alarm Control Panel. Where a fire detection system is installed in accordance with the requirements of 7.4.7.1, an approved fire alarm control panel (FACP) shall be provided in accordance with Chapters 10 and 14 of *NFPA 72*, or other equivalent international standards.

N **7.4.7.1*** The FACP shall be used to receive signals from the facilities' automatic fire detection system and to initiate alarms.

7.5* Emergency Communications Systems — Two-Way Radio Communication Enhancement System.

7.5.1 Two-way radio communication enhancement systems shall be installed in new and existing tunnels and ancillary facilities where required by the AHJ or by other applicable governing laws, codes, or standards.

7.5.2 Two-way radio communication enhancement systems shall be designed, installed, tested, and maintained in accordance with the provisions of Chapter 24 of *NFPA 72*.

7.6 Tunnel Closure and Traffic Control.

7.6.1 All road tunnels, as defined by this standard, shall be provided with a means to stop approaching traffic.

7.6.2 Road tunnels longer than 240 m (800 ft) shall be provided with means to stop traffic from entering the direct approaches to the tunnel, to control traffic within the tunnel, and to clear traffic downstream of the fire site following activation of a fire alarm within the tunnel. The following requirements shall apply:

(1) Direct approaches to the tunnel shall be closed following activation of a fire alarm within the tunnel. Approaches shall be closed in such a manner that responding emergency vehicles are not impeded in transit to the fire site.
(2) Traffic within the tunnel approaching (upstream of) the fire site shall be stopped prior to the fire site until it is safe to proceed as determined by the incident commander.
(3)* Means shall be provided downstream of an incident site to expedite the flow of vehicles from the tunnel. If it is not possible to provide such means under all traffic conditions, then the tunnel shall be protected by a fixed water-based fire-fighting system or other suitable means to establish a tenable environment to permit safe evacuation and emergency services access.
(4) Operation shall be returned to normal as determined by the incident commander.

Δ **7.7* Fire Apparatus. (Reserved)**

7.8* Standpipe, Fire Hydrants, and Water Supply. Standpipe and water supply systems in road tunnels shall be provided in accordance with the requirements of Chapter 10.

7.9* Portable Fire Extinguishers.

7.9.1 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).

7.9.2 To facilitate safe use by motorists, the maximum weight of each extinguisher shall be 9 kg (20 lb).

7.9.3 Portable fire extinguishers shall be selected, installed, inspected, and maintained in accordance with NFPA 10.

7.10 Fixed Water-Based Fire-Fighting Systems. See Chapter 9.

7.10.1 Fixed water-based fire-fighting systems shall be conditionally mandatory in category C and category D tunnels.

7.11 Emergency Ventilation. Tunnel ventilation systems employed during fire emergencies shall comply with the requirements of Chapter 11.

7.12* Tunnel Drainage System.

7.12.1* A drainage system shall be provided in tunnels to collect, store, or discharge effluent from the tunnel, or to perform a combination of these functions.

7.12.2* The drainage collection system shall be designed to capture spills of hazardous or flammable liquids so that they cannot spread or cause flame propagation such that the length of the road surface drain path from any potential spill point to the drain inlet(s) is minimized.

7.12.3 Components of the drainage conveyance and collection system, including the main drain lines, shall be noncombustible (e.g., steel, ductile iron, or concrete).

7.12.4* The drainage system shall be constructed entirely of noncombustible materials.

7.12.5* The drainage conveyance and collection system shall have sufficient capacity to receive, as a minimum, the rate of flow from all design roadway sources without causing flooding of the roadway.

7.12.5.1 The minimum design flow rate shall include, where applicable, the design spill rate for fuel or other hazardous liquids, the standpipe system discharge rate, any fixed water-based fire-fighting system discharge rate, environmental sources (rain, snow, etc.), tunnel washing, and any other catchments sharing the tunnel drainage system piping.

7.12.5.2* Where the tunnel roadway drainage system discharges by gravity or by pumped discharge, it shall be provided with a separator, drainage storage capacity, or combination sufficient for the design spill rate for the hazardous liquids.

7.12.6 Hazardous Locations.

7.12.6.1 Storage tanks and wet wells and service chambers of pump stations shall be classified for hazardous locations in accordance with *NFPA 70* and NFPA 820.

7.12.6.2 All motors, starters, level controllers, system controls, and other miscellaneous electrical equipment, such as components of the lighting system in the pump station, shall conform to the requirements of the hazard classification.

7.12.7 Hydrocarbon Detection.

7.12.7.1 Storage tanks and pump stations shall be monitored for hydrocarbons.

7.12.7.2 Detection of hydrocarbons in the tunnel drainage effluent shall initiate both a local and a remote alarm.

Δ **7.13* Alternative Fuels. (Reserved)**

7.14 Control of Hazardous Materials. Control of hazardous materials shall comply with the requirements of Chapter 14.

7.14.1* Fire size, growth rate, and smoke release rate shall be permitted to be reduced where an engineering analysis can show that the pool size of the combustible or flammable liquid can be limited by proper design of the roadway cross slope, the roadway grade, the drainage inlets, and the drainage conveyance pipe or trough.

7.14.1.1 If fire is to be controlled by drainage method(s), this shall be coordinated with tunnel drainage in accordance with Section 7.12.

7.15* Flammable and Combustible Environmental Hazards.

7.15.1 Design, construction, maintenance, and operation of tunnels shall consider the flammable and combustible risks for both naturally occurring and constructed environmental hazards from outside the road tunnel.

7.15.2 For the identified hazards, an engineering analysis shall be performed of constructed or naturally occurring environmental sources of fire-life safety hazards to determine means and methods for mitigation of identified risks to tunnel fire-life safety.

7.16 Means of Egress.

7.16.1 General.

Δ **7.16.1.1*** The means of egress requirements for all road tunnels and those roadways beneath air-right structures that the AHJ determines are similar to a road tunnel shall be in accordance with NFPA *101*, Chapter 7, except as modified by this standard.

7.16.1.2* Reflective or lighted directional signs indicating the distance to the two nearest emergency exits shall be provided on the side walls at distances of no more than 25 m (82 ft).

N **7.16.1.3*** Wayfinding shall be provided to aid evacuation of the tunnel.

N **7.16.1.3.1** The type and extent of wayfinding shall be determined by an engineering analysis.

N **7.16.1.3.2** Where wayfinding lighting is used, it shall be in accordance with Section 12.8.

7.16.2* Tenable Environment. A tenable environment shall be provided in the means of egress during the evacuation phase in accordance with the emergency response plan for a specific incident. The criteria for tenability and time of tenability shall be established.

7.16.3 Maintenance. The means of egress shall be maintained in accordance with NFPA 1.

7.16.4 Walking Surfaces.

7.16.4.1 The walking surfaces of the emergency exits, cross-passageways, and walkways shall be slip resistant.

Δ **7.16.4.2** Changes in elevation, ramps, and stairs shall meet the requirements of Chapter 7 of NFPA *101*.

7.16.5 Emergency Exit Doors.

7.16.5.1* Emergency exit doors shall provide protection against fire and ensure pressurization of escape routes.

7.16.5.2 Doors to the emergency exits shall open in the direction of exit travel.

7.16.5.3 Horizontal sliding doors shall have a sign identifying them as horizontal sliding doors and indicating the direction to open.

7.16.5.4* Horizontal sliding doors shall be permitted in emergency exits.

7.16.5.5* Emergency exit door assemblies exposed to the incident tunnel shall be 1½-hour rated, based on the time-temperature curve described in 7.3.2, and shall be installed in accordance with NFPA 80. All other doors in the path of egress shall comply with NFPA *101*.

7.16.5.6* 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). This opening force shall not be exceeded under the worst-case ventilation differential pressure.

7.16.5.7* Emergency exit doors and associated hardware shall be designed to withstand positive and negative pressures created by passing vehicles.

7.16.5.8 Emergency exit doors shall be self-closing door systems and shall not rely on external power.

Δ **7.16.6 Emergency Exits.**

7.16.6.1* Emergency exits shall be provided throughout the tunnel.

7.16.6.2* Spacing between exits for protection of tunnel occupants shall not exceed 300 m (1000 ft). Required spacing shall be determined by consideration of the following factors:

(1) Category, including types and classes of tunnels
(2) Design fire scenario
(3) Egress analysis
(4) Fire-life safety systems analyses to provide tenable environment in tunnel in accordance with 7.16.2 (This includes type and operation of tunnel ventilation, detection, fire protection, and control systems.)
(5) Traffic management system
(6) Emergency response plan
(7) Consideration of uncertainties of people's behavior during a fire event and of those who are unable to self-rescue

7.16.6.3* Egress Pathway.

7.16.6.3.1* The tunnel roadway surface, when supported by a traffic management system, shall be considered as a part of the egress pathway.

7.16.6.3.2 The egress pathway shall have a minimum clear width of 1.12 m (3.7 ft), lead directly to an emergency exit, and be protected from traffic.

7.16.6.4* The emergency exits shall be separated from the tunnel by a minimum of a 2-hour fire-rated construction enclosure, rated based on the time-temperature curve described in 7.3.2.

7.16.6.5 Emergency "exits" shall be pressurized in accordance with NFPA 92 with doors meeting the requirements of 7.16.5.

7.16.6.6* Where portals of the tunnel are below surface grade, surface grade shall be made accessible by a stair, vehicle ramp, or pedestrian ramp.

7.16.6.7 Where cross-passageways are used as an emergency exit, provisions shall be included that stop all traffic operation in the adjacent tunnel.

7.17 Acceptance Test.

7.17.1 Acceptance tests for fire alarm and detection systems shall be performed in accordance with Chapters 7 and 14 of *NFPA 72*, or other equivalent international standards, including performance requirements specified in the basis of design.

7.17.2 Acceptance tests for standpipe systems shall be performed in accordance with NFPA 14 or other equivalent international standards and performance specified in Chapter 10.

7.17.3 Acceptance tests for water-based fire-fighting systems shall be performed in accordance with NFPA 11, NFPA 13, NFPA 15, NFPA 16, NFPA 18, NFPA 18A, and NFPA 750 or other equivalent international standards as applicable to the system(s) installed, including performance requirements specified in the basis of design.

7.17.4 Acceptance tests for fire hydrants, water mains, and water supply systems shall be performed in accordance with NFPA 22, NFPA 24, or other equivalent international standards as applicable to the system(s) installed and performance specified in Chapter 10.

7.17.5 Acceptance tests for emergency ventilation systems shall be performed in accordance with the basis of design criteria, equipment manufacturers' specifications, agreed-upon methods acceptable to the AHJ, and performance requirements specified in Chapter 11.

Δ **7.17.6** Acceptance tests for electrical systems (emergency power, emergency lighting, exit signs, etc.) shall be performed in accordance with *NFPA 70*, NFPA 110, basis of design criteria, equipment manufacturers' specifications, and performance requirements specified in Chapter 12.

7.17.7 Acceptance tests for communication systems and traffic control systems shall be performed in accordance with the basis of design, equipment manufacturers' specifications, and agreed-upon methods acceptable to the AHJ.

Chapter 8 Roadways Beneath Air-Right Structures

8.1* General. This chapter shall provide fire protection and life safety requirements for roadways where a structure is built using the air rights above the road.

8.2 Application. Where required by the authority having jurisdiction (AHJ), the requirements of Chapter 4 shall apply.

8.2.1 The limits that an air-right structure imposes on the emergency accessibility and function of the roadway that is located beneath the structure shall be assessed.

8.2.2 Where an air-right structure encloses both sides of a roadway, it shall be considered a road tunnel for fire protection purposes and shall comply with the requirements of Chapter 7.

8.2.3* Where an air-right structure does not fully enclose the roadway on both sides, the decision to consider it as a road tunnel shall be made by the AHJ after an engineering analysis in accordance with 4.3.1.

8.3 Traffic Control.

8.3.1 Where the roadway beneath an air-right structure is considered a road tunnel, the traffic-control requirements of Section 7.6 shall apply.

8.3.2 The traffic-control system shall be interlocked with the fire alarm system in such a manner that the control system can be operated from either a remote source or from either end of the roadway that passes beneath the air-right structure.

8.4 Protection of Structure.

8.4.1 All structural elements that support air-right structures over roadways and all components that provide separation between air-right structures and roadways shall have a minimum 2-hour fire resistance rating in accordance with Section 7.3.

8.4.1.1* An engineering analysis shall be prepared to determine acceptable risk to include possible collapse scenarios of the air-right structure(s).

8.4.2 Structural members shall be protected from physical damage from vehicle impact. An inspection and repair program shall be kept in force to monitor and maintain the structure and its protection.

8.4.3 Maintenance of the structure shall be considered in the design.

8.4.4 Structural support elements shall not be within the dynamic vehicle envelope.

8.4.5 Buildings that are located above roadways shall be designed with consideration of the roadway below an air-right structure as a potential source of heat, smoke, and vehicle emissions.

8.4.6 The structural elements shall be designed to shield the air-right structure and its inhabitants from these potential hazards.

8.4.7 The design of the air-right structure shall neither increase risk nor create any risk to those who use the roadway below.

8.5 Emergency Ventilation.

8.5.1 Chapter 11 shall apply where ventilation during a fire emergency within the roadway beneath an air-right structure is required by Section 7.2.

8.5.2 The prevention or minimization of adverse effects on air-right structures and their occupants from fire products such as heat, smoke, and toxic gases shall be considered in the design of the ventilation system.

8.6 Drainage System. Where required by the AHJ, a drainage system that is designed in accordance with the requirements of Section 7.12 shall be provided for roadways beneath air-right structures.

8.7 Control of Hazardous Materials. Control of hazardous materials shall comply with the requirements of Chapter 14.

8.8 Emergency Response Plan.

8.8.1 Where an air-right structure includes a building or facility, a mutual emergency response plan shall be developed among the operator of the air-right structure, the operator of the roadway, and the local AHJ so that, during an emergency in either the air-right structure or the roadway, the safety of the motorists using the roadway and of the occupants of the air-right structure is enhanced.

8.8.2 Emergency response procedures and the development of emergency response plans shall comply with the requirements of Chapter 13.

8.9* Standpipe, Fire Hydrants, and Water Supply. Where the roadway beneath air-right structure length is 90 m (300 ft) or greater, standpipe and water supply systems shall be provided in accordance with the requirements of Chapter 10.

8.10 Acceptance Test.

8.10.1 Acceptance tests for standpipe systems shall be performed in accordance with NFPA 14 or other equivalent international standards and performance specified in Chapter 10.

8.10.2 Acceptance tests for fire hydrants, water mains, and water supply systems shall be performed in accordance with NFPA 22, NFPA 24, or other equivalent international standards as applicable to the system(s) installed and performance specified in Chapter 10.

8.10.3 Acceptance tests for emergency ventilation systems shall be performed in accordance with the basis of design criteria, equipment manufacturers' specifications, agreed-upon methods acceptable to the AHJ, and performance requirements specified in Chapter 11.

8.10.4 Acceptance tests for communication systems and traffic control systems shall be performed in accordance with the basis of design, equipment manufacturers' specification, and agreed-upon methods acceptable to the AHJ.

Chapter 9 Fixed Water-Based Fire-Fighting Systems

9.1* General.

9.1.1 Fixed water-based fire-fighting systems (FFFS) shall be permitted in road tunnels as part of an integrated approach to the management of fire protection and fire-life safety risks.

9.1.2 When an FFFS is installed in road tunnels, it shall be installed, inspected, and maintained in accordance with NFPA 11, NFPA 13, NFPA 15, NFPA 16, NFPA 18, NFPA 18A, NFPA 25, NFPA 750, or other equivalent international standard.

9.2 Design Objectives.

Δ **9.2.1** The goal of an FFFS shall be to slow, stop, or reverse the fire growth rate or otherwise mitigate the impact of fire to improve tenability for tunnel occupants during a fire condition, enhance the ability of first responders to aid in evacuation and engage in manual fire-fighting activities, and/or protect the major structural elements of a tunnel.

9.2.2* Fixed water-based fire-fighting systems shall be categorized based upon their desired performance objective in 9.2.2.1 through 9.2.2.4.

9.2.2.1* Fire Suppression System. A fire suppression system shall be a fixed water-based system intended to sharply reduce the heat release rate of a fire and prevent its growth by means of direct and sufficient application of extinguishing agent through the fire plume to the burning fuel surface.

9.2.2.2* Fire Control System. A fire control system shall be a fixed water-based system intended to limit the size of a fire by distribution of extinguishing agent to decrease the heat release rate and pre-wet adjacent combustibles while controlling gas temperatures to avoid structural damage.

9.2.2.3* Volume Cooling System. A fixed water-based system shall be designed to provide substantial cooling of products of combustion but is not intended to affect heat release rate directly.

9.2.2.4* Surface Cooling System. A fixed water-based system shall be designed to provide direct cooling of critical structure, equipment, or appurtenances without directly affecting heat release rate.

N **9.3 Water Supply.**

N **9.3.1** FFFS shall be connected to an approved water supply that is capable of supplying system demand for a minimum of 1 hour.

N **9.3.2** The water supply demand for a facility with an FFFS shall include the demand for the FFFS and the standpipe system when both systems are provided.

N **9.3.3** Acceptable water supplies shall include the following:

(1) Municipal or privately owned waterworks systems that have adequate pressure and flow rate and a level of integrity acceptable to the authority having jurisdiction (AHJ)
(2) Automatic or manually controlled fire pumps that are connected to an approved water source
(3) Pressure-type or gravity-type storage tanks that are installed, inspected, and maintained in accordance with NFPA 22

9.4 Performance Evaluation.

9.4.1 Fire test protocols shall be designed to address the performance objectives as described in 9.2.2 and the tunnel parameters described in Section 9.5.

9.4.2* Fire test protocols shall be designed to replicate and evaluate the range of the application parameters associated with road tunnels.

9.4.3* System components shall be listed or as approved by the AHJ.

9.4.4 Impact on Other Safety Measures.

9.4.4.1 For the sizing of the emergency ventilation system in accordance with Section 11.4, the effect of the fixed water-based fire-fighting system shall be taken into account.

9.4.4.2 For protection of structural elements, the applicable provisions of Section 7.3 shall apply unless evidence of the performance of the required structural fire protection by a fixed water-based fire-fighting system is provided and approved by the AHJ.

9.4.5 Layout Parameters. To achieve the design objectives in accordance with 9.2.1, discharge device coverage, spacing, positioning, spray characteristics, working pressure, and flow rates shall be determined by use of applicable codes, standards, or accepted practices, or where necessary, by an engineering analysis considering relevant available data resulting from full-scale tunnel fixed water-based fire-fighting tests of the type of fixed water-based fire-fighting system being used.

9.5 Tunnel Parameters.

9.5.1 *Tunnel parameters* shall be the features of the tunnel that affect the design of a water-based fire-fighting system.

9.5.2 Tunnel Geometry. The tunnel geometry (width, ceiling height, obstruction location) shall be considered when selecting such parameters as nozzle location and nozzle positioning.

9.5.3 Ventilation. Ventilation considerations shall include natural and fire-induced forced ventilation parameters.

9.5.4 Hazard Analysis. A fire hazard analysis shall be conducted to determine both the design parameters of the water-based fire-fighting system and the type of detection and activation scheme employed. The water-based fire-fighting system shall address the anticipated vehicle types and contents, ease of ignition and re-ignition of the fuel, anticipated fire growth rate, and difficulty of achieving one or more of the performance objectives established in Section 9.2 or as otherwise acceptable to the AHJ.

9.5.5 Obstructions and Shielding. The presence of obstructions and the potential for shielding of water-based fire-fighting system discharge shall be addressed to ensure that system performance is not affected.

9.5.6 Ambient Conditions. The range of ambient conditions that could be experienced in the tunnel shall be identified.

9.6 System Design and Installation Documentation.

9.6.1 The system design and installation documentation shall identify the design objectives and tunnel parameters over which the system performance evaluation is valid.

9.6.2 System documentation shall clearly identify engineering safety factors incorporated into the overall system design. Safety factors shall be required to ensure that installed system performance exceeds the performance of the system as tested in accordance with Section 9.4.

9.6.3 System documentation shall also include recommended testing, inspection, and maintenance procedures and, by reference, the requirements of the relevant NFPA standard or equivalent standard acceptable to the AHJ.

9.7 Engineering Design Requirements.

9.7.1* When an FFFS is included in the design of a road tunnel, the impact of this system on other measures that are part of the overall safety concept shall be evaluated. At a minimum, this evaluation shall address the following:

(1) Impact on drainage requirements
(2) Impact on tenability, including the following:
   (a) Increase in humidity
   (b) Reduction (if any) in stratification and visibility
(3) Integration with other tunnel systems, including the following:
   (a) Fire detection and alarm system
   (b) Tunnel ventilation system
   (c) Traffic control and monitoring systems
   (d) Visible emergency alarm notification
   (e) Protection of structural elements
(4) Incident command structure and procedures, including the following:
   (a) Procedures for tunnel operators
   (b) Procedures for first responders
   (c) Tactical fire-fighting procedures
(5) Protection and reliability of the FFFS, including the following:
   (a) Impact events
   (b) Seismic events
   (c) Redundancy requirements
(6) Ongoing system maintenance, periodic testing, and service requirements

9.7.2 The engineering analysis shall also address delays in activation.

Δ Chapter 10 Standpipe Systems

Δ 10.1 General.

10.1.1 Standpipe systems shall be designed and installed as Class I systems in accordance with NFPA 14, except as modified by this standard.

10.1.2 Standpipe systems shall be inspected and maintained in accordance with NFPA 25.

10.1.3 Standpipe systems shall be either wet or dry, depending on the climatic conditions, the fill times, the requirements of the authority having jurisdiction (AHJ), or any combination thereof.

10.1.4 Areas Subject to Freezing.

10.1.4.1 Where wet standpipes are required in areas subject to freezing conditions, the water shall be heated and circulated.

10.1.4.2 All piping and fittings that are exposed to freezing conditions shall be heat-traced and insulated.

10.1.4.3 Heat trace material shall be listed for the intended purpose and supervised for power loss.

10.1.5* Dry standpipe systems shall be installed in a manner so that the water is delivered to all hose connections on the system in 10 minutes or less.

10.1.6 Combination air relief–vacuum valves shall be installed at each high point on the system.

10.2 Water Supply.

10.2.1 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 hour.

10.2.2 Dry standpipe systems shall have an approved water supply that is capable of supplying the system demand for a minimum of 1 hour.

10.2.3 Acceptable water supplies shall include the following:

(1) Municipal or privately owned waterworks systems that have adequate pressure and flow rate and a level of integrity acceptable to the AHJ
(2) Automatic or manually controlled fire pumps that are connected to an approved water source
(3) Pressure-type or gravity-type storage tanks that are installed, inspected, and maintained in accordance with NFPA 22

10.3 Fire Department Connections.

10.3.1 Fire department connections shall be of the threaded two-way, three-way, or four-way type or shall consist of at least one minimum 100 mm (4 in.) quick-connect coupling that is accessible and compatible with responding fire department equipment or as approved.

10.3.2 Each independent standpipe system shall have a minimum of two fire department connections that are remotely located from each other.

10.3.3 Fire department connections shall be protected from vehicular damage by means of bollards or other approved barriers.

10.3.4 Fire department connection locations shall be approved and shall be coordinated with emergency access and response locations.

10.4 Hose Connections.

10.4.1 Hose connections shall be spaced so that no location on the protected roadway is more than 45 m (150 ft) from the hose connection.

10.4.2* Hose connection spacing shall not exceed 85 m (275 ft).

10.4.3 Hose connections shall be located so that they are conspicuous and convenient but still reasonably protected from damage by errant vehicles or vandals.

10.4.4 Hose connections shall have 65 mm (2½ in.) external threads in accordance with NFPA 1963 and the AHJ.

10.4.5 Hose connections shall be equipped with caps to protect hose threads.

10.5 Fire Pumps. Fire pumps shall be installed, inspected, and maintained in accordance with NFPA 20.

10.6 Identification Signs.

10.6.1 Identification signage for standpipe systems and components shall be approved by and developed with input from the AHJ.

10.6.2 Identification signage shall, as a minimum, identify the name and limits of the roadway that is served.

10.6.3 Identification signage shall be conspicuous and shall be affixed to, or immediately adjacent to, fire department connections and each roadway hose connection.

Chapter 11 Emergency Ventilation

11.1* General. Emergency ventilation systems and tunnel operating procedures shall be developed to maximize the use of the road tunnel ventilation system for the removal and control of smoke and heated gases that result from fire emergencies within the tunnel.

11.1.1* Emergency ventilation shall not be required in tunnels less than 1000 m (3280 ft) in length, where it can be shown by an engineering analysis, using the design parameters 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 (AHJ).

11.1.2 Emergency ventilation shall be required in tunnels exceeding 1000 m (3280 ft).

11.1.3 For any engineering analysis performed to determine the requirement for tunnel emergency ventilation, potential fires immediately proximate to the tunnel portal, but outside the tunnel, that can have a negative impact on the tunnel environment shall be included in the engineering analysis.

11.1.4* The emergency ventilation operational procedures shall be designed to assist in the evacuation or rescue, or both, of motorists from the tunnel.

11.1.5 Emergency ventilation shall be sized to meet minimum ventilation requirements with one fan out of service or shall provide operational measures to ensure that life safety is not compromised with one fan out of service.

Δ **11.2* Smoke Control.**

11.2.1 The emergency ventilation system shall provide a means for controlling smoke.

11.2.2 In all cases, the desired goal shall be to provide an evacuation path for motorists who are exiting from the tunnel and to facilitate fire-fighting operations.

11.2.3 In tunnels with bidirectional traffic where motorists can be on both sides of the fire site, the following objectives shall be met:

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

Δ **11.2.4*** 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 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.
(2) Transverse or reversible semitransverse 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.

11.3 Design Objectives. The design objectives of the emergency ventilation system shall be to control, to extract, or to control and extract smoke and heated gases as follows:

(1) A stream of noncontaminated air is provided to motorists in path(s) of egress in accordance with the anticipated emergency response plan *(see Annex C)*.
(2) Longitudinal airflow rates are produced to prevent backlayering of smoke in a path of egress away from a fire *(see Annex D)*.

11.4* Basis of Design. The design of the emergency ventilation system shall be based on a fire scenario having defined heat release rates (HRR), smoke release rates, and carbon monoxide release rates, all varying as a function of time. The selection of the fire scenario shall consider the operational risks that are associated with the types of vehicles expected to use the tunnel. The fire scenario shall consider fire at a location where the most stringent ventilation system performance requirement is anticipated by an engineering analysis.

11.4.1* The design fire scenario shall be used to design the emergency ventilation system.

11.4.2* The selection of the design fire scenario shall consider the types of vehicles that are expected to use the tunnel and whether the tunnel is fitted with other fire-life safety systems including, but not limited to, FFFS, fire detection systems, and activation systems, and whether the other fire-life safety systems allow for mitigation of the design fire scenario.

11.4.3* Failure or loss of availability of emergency ventilation equipment shall be considered.

11.5 Fans.

11.5.1* Tunnel ventilation fans, their motors, and all components critical to the operation of the system during a fire emergency that can be exposed to elevated temperatures from the fire shall be designed to remain operational for a minimum of 1 hour at a temperature of 250°C (482°F).

11.5.1.1 Where design calculations carried out as required in Section 11.4 show higher temperatures, those higher temperatures shall be used for equipment selection.

11.5.2 Tunnel ventilation fans, such as jet fans, that can be directly exposed to fire within the tunnel roadway shall be considered expendable.

11.5.3* The design of ventilation systems where fans can be directly exposed to a fire shall incorporate fan redundancy.

11.5.4 The emergency ventilation system shall be capable of reaching full operational mode within a maximum of 180 seconds of activation.

11.5.5 Reversible fans shall be capable of completing full rotational reversal within 90 seconds.

11.5.6 Discharge and outlet openings for emergency fans shall be positioned away from any supply air intake openings to prevent recirculation.

11.5.7 Where separation is not possible, intake openings shall be protected by other approved means or devices to prevent smoke from re-entering the system.

11.6 Dampers.

11.6.1 All dampers, actuators, and accessories that are exposed to the elevated exhaust airstream from the roadway fire shall be designed to remain fully operational in an airstream temperature of 250°C (482°F) for at least 1 hour.

11.6.1.1 Where design calculations carried out as required in Section 11.4 show higher temperatures, those higher temperatures shall be used for equipment selection.

11.6.2 All moving and other critical components of the damper shall be designed to allow for expansion and contraction throughout the maximum anticipated temperature range.

11.6.3 The bearings of multibladed dampers shall be located outside of the airstream.

11.6.4 The actuators and bearings shall be isolated from the heated airstream.

11.6.5 The requirements of 11.6.3 and 11.6.4 shall not apply where the application warrants a special type of bearing, or where it is impossible to locate the bearings in a position that is clear of the airstream, as in the case of single-point extraction dampers.

11.6.6 All other dampers designed for use during a fire emergency shall be equipped with power actuators that are capable of being manually or automatically controlled.

11.7 Sound Attenuators.

11.7.1 Sound attenuators that are located in the elevated airstream from the roadway, such as those used in semitransverse exhaust systems and fully transverse exhaust ducts, shall be capable of withstanding an airstream temperature of 250°C (482°F).

11.7.1.1 Where design calculations carried out as required in Section 11.4 show higher temperatures, those higher temperatures shall be used for equipment selection.

11.7.1.2 All components of the attenuator shall remain structurally intact and in place after the required 1 hour of operation.

11.7.2 The sound-absorbing fill material used in the baffles shall be noncombustible, nontoxic, and stable at the temperatures specified in 11.7.1.

11.8 Controls.

11.8.1 The fans shall be locally controllable in addition to any automatic or remote control so that the equipment can be manually operated. Where both the local and remote controls provide the capability to operate the fans in an emergency mode, local control shall be capable of overriding remote control.

11.8.1.1 Local control shall be the switching devices at the motor control.

11.8.2 Control devices including motor starters, motor drives, and motor disconnects shall be isolated from the fan airstream to the greatest extent practical.

11.9 Flammable and Combustible Liquids Intrusion.

11.9.1 General. Prevention of accidental intrusion of flammable and combustible liquids due to spills shall be provided in accordance with 11.9.2 and 11.9.3.

11.9.2 Vehicle Roadway Terminations. Vent or fan shafts utilized for ventilation of tunnels shall not terminate at grade on any vehicle roadway.

11.9.3 Median and Sidewalk Terminations. Vent and fan shafts shall be permitted to terminate in the median strips of divided highways, on sidewalks designed to accept such shafts, or in open space areas, provided that the following conditions are met:

(1) The grade level of the median strip, sidewalk, or open space is at a higher elevation than the surrounding grade level.
(2) The grade level of the median strip, sidewalk, or open space is separated from the roadway by a concrete curb at least 152.4 mm (6 in.) in height.

Chapter 12 Electrical Systems

12.1 General.

12.1.1* The electrical systems shall support life safety operations, fire emergency operations, and normal operations.

Δ **12.1.2** Emergency circuits installed in a road tunnel and ancillary areas shall remain functional for a period of not less than 1 hour for the anticipated fire condition by one of the following methods:

(1)* Fire-resistive cables shall be approved or listed for no less than 2 hours when tested to the time-temperature curve of ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*, in accordance with ANSI/UL 2196, *Standard for Fire Test for Circuit Integrity of Fire-Resistive Power, Instrumentation, Control, and Data Cables*, or other approved, recognized standards, as follows:
   (a) Fire-resistive cables shall be tested as a complete system, in both vertical and horizontal orientations, on conductors, cables, and raceways as applicable.
   (b) Fire-resistive cables intended for installation in a raceway shall be tested in the type of raceway in which they are intended to be installed.
   (c) Each fire-resistive cable system shall have installation instructions that describe the tested assembly with only the components included in the tested assembly acceptable for installations.
(2)* Circuits shall be protected by a 2-hour fire barrier system in accordance with UL 1724, *Outline of Investigation for Fire Tests for Electrical Circuit Protective Systems*. The cables or conductors shall maintain functionality at the operating temperature within the fire barrier system.
(3) They shall remain functional by the routing of the cable system external to the roadway
(4) They shall remain functional by using diversity in system routing as approved, such as separate redundant or multiple circuits separated by a 2-hour fire barrier, so that a single fire or emergency event will not lead to a failure of the system.

12.1.3 The requirement of 12.1.2 shall not apply to bidirectional antennas used for emergency communication circuits.

12.1.4 The electrical systems shall maintain ventilation, lighting, communications, drainage, a fixed water-based fire-extinguishing system, fire alarm and fire detection, exit signs, traffic control, and others for areas of refuge, exits, and exit routes, under all normal and emergency modes associated with the facility.

12.1.5* The fire-life safety electrical systems shall be designed and installed to resist lateral forces induced by earthquakes (seismic forces) in the appropriate seismic zone and to continue to function after the event.

12.1.6 An electrical single-line diagram shall be posted within the main electrical room.

12.1.6.1 The diagram shall include utility short-circuit duty, all sources, uninterrupted power supplies (UPSs), or standby source and interlocking schemes, and other data per IEEE standards for single-line diagrams.

12.1.7 Labels, nameplates, or tags shall be affixed to switchboards, panelboards, motor controllers, switches, and breakers that correspond to the single line. The equipment or device operating instructions shall be available to operating personal.

12.2 Wiring Methods.

12.2.1 All wiring materials and installations shall conform to *NFPA 70* except as herein modified in this standard.

12.2.1.1 All cables and conductors shall be of the moisture-resistant and heat-resistant types with temperature ratings that correspond to the conditions of application.

12.2.1.2 All cables and conductors shall be listed for use in wet locations.

Δ **12.2.1.3** All cables and conductors used in road tunnels shall be resistant to the spread of fire and shall have reduced smoke emissions by one of the following methods:

(1) Wires and cables listed as having fire-resistant and low smoke-producing characteristics, by having a cable char height of not greater than 1.5 m (4.9 ft) when measured from the lower edge of the burner face, a total smoke release over the 20-minute test period no greater than 150 m^2, and a peak smoke release rate of no greater than 0.40 m^2/sec, when tested in accordance with either the IEEE 1202 method described in ANSI/UL 1685, *Vertical-Tray Fire-Propagation and Smoke-Release Test for Electrical and Optical-Fiber Cables*, or the CSA FT4, Vertical Flame Test, per CSA C22.2 No. 0.3, *Test Methods for Electrical Wires and Cables*.
(2) Wires and cables listed as having fire-resistant and low smoke-producing characteristics, by having a flame travel distance that does not exceed 1.5 m (4.9 ft), generating a maximum peak optical density of smoke of 0.5 and a maximum average optical density of smoke of 0.15 when tested in accordance with the methods described in NFPA 262 or in CSA FT6, Horizontal Flame and Smoke Test, per CSA C22.2 No. 0.3.
(3) Wires and cables tested to equivalent internationally recognized standards approved by the authority having jurisdiction (AHJ).

12.2.1.4 All cables and conductors used in road tunnels shall emit less than 2 percent acid gas when tested in accordance with MIL-DTL-24643C, *Detail Specification: Cables, Electric, Low Smoke Halogen-Free, for Shipboard Use,* or in accordance with an equivalent internationally recognized standard approved by the AHJ.

Δ **12.3 Installation Methods.**

12.3.1 Cables and conductors shall be protected by means of metallic armor/sheath, metal raceways, electrical duct banks embedded in concrete, or other approved methods except as otherwise permitted by 12.3.1.1 or 12.3.1.2.

12.3.1.1 Cables and conductors installed in ancillary facilities shall not require additional physical protection as described in 12.3.1 provided that they are installed in a cable tray and are listed for cable tray use.

12.3.1.2 Nonmetallic raceways shall be permitted when installing cables and conductors on limited access highways, road tunnels, bridges, elevated highways, depressed highways, and roadways that are located beneath air-right structures.

12.3.2 Raceways, equipment, and supports installed in a road tunnel and ancillary areas shall comply with the following:

(1) Exposed raceways, equipment, and supports with combustible outer coverings or coatings shall emit less than 2 percent acid gas when tested in accordance with MIL-DTL-24643C, *Detail Specification: Cables, Electric, Low Smoke Halogen-Free, for Shipboard Use*, or with an approved, equivalent, internationally recognized standard.
(2) Nonmetallic conduits shall be permitted when covered with a minimum of 100 mm (4 in.) concrete when approved. All conduit ends inside of pull boxes and junction boxes shall be firestopped.
(3) Nonmetallic raceways used in road tunnels shall meet a flame spread index not exceeding 25 and a smoke developed index not exceeding 50 when tested in accordance with ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials*, or shall be noncombustible per Section 4.8.

12.3.3* All wiring and cables installed in supply air ducts shall meet one of the following:

(1) Shall be listed as having fire-resistant and low smoke-producing characteristics exhibiting a maximum peak optical density of 0.5 or less, an average optical density of 0.15 or less, and a maximum flame spread distance of 1.5 m (4.9 ft) or less when tested, as a minimum, in accordance with NFPA 262 or with CSA FT6 Horizontal Flame and Smoke Test, per CSA C22.2 No. 0.3, *Test Methods for Electrical Wires and Cables*.
(2) Shall be installed in nonmetallic conduits that are embedded in concrete with all conduit ends firestopped where they enter pull boxes or splice boxes
(3) Shall be installed in intermediate metal conduit, or rigid metal conduit without an overall nonmetallic covering, or flexible metallic tubing no longer than 6 ft in length
(4) Shall be Type MI cable, or Type MC cable employing a smooth or corrugated impervious metal sheath without an overall nonmetallic covering

12.3.3.1 All equipment and supports installed in supply air ducts shall be metallic without nonmetallic coverings.

12.3.4* Conduits, equipment, and supports installed in exhaust air ducts that can be exposed to elevated temperatures shall be metallic without nonmetallic covering. Where nonmetallic conduit is permitted by the AHJ, it shall be embedded in concrete with all conduit ends firestopped where they enter pull boxes or splice boxes.

12.3.5 Labels, or tags, shall be affixed to essential circuit feeders with numbering that is consistent with the posted single line diagram of 12.1.6.

Δ **12.4 Emergency Power.** Road tunnels complying with Category B–D in Section 7.2 shall be provided with emergency power in accordance with Article 700 of *NFPA 70*. (*For emergency and standby power systems other than separate service, see NFPA 110.*)

12.4.1 The following systems shall be connected to the emergency power system:

(1) Emergency lighting
(2) Tunnel closure and traffic control
(3) Exit signs
(4) Emergency communication
(5) Tunnel drainage
(6) Emergency ventilation
(7) Fire alarm and detection
(8) Closed-circuit television or video
(9) Fire fighting

12.5* Reliability.

12.5.1 The electrical systems of tunnels and dual-level bridges in excess of 1000 m (3280 ft) in length shall have redundant facilities for the purpose of monitoring and control.

12.5.2 The electrical systems shall be designed to allow for routine maintenance without disruption of traffic operation.

12.5.3 Wiring in manholes shall be protected from spillage of flammable liquids or fire-fighting products by the installation of manhole covers with sealing and locking capability.

12.5.4 Conductors in manholes shall be protected from spillage of flammable liquids or fire-fighting products by the installation of manhole covers with sealing and locking capability.

12.6 Emergency Lighting.

12.6.1* Emergency lighting systems shall be installed and maintained in accordance with *NFPA 70*, NFPA 110, and NFPA 111.

12.6.2 Emergency lights, exit lights, and essential signs shall be included in the emergency lighting system and shall be powered by an emergency power supply.

12.6.3 Emergency luminaires, exit lights, and signs shall be wired from emergency distribution panels in separate raceways.

12.6.4 Emergency lighting levels for roadways and walkways shall be maintained in those portions of the tunnel that are not involved in an emergency.

12.6.5* There shall be no interruption of the lighting levels for greater than 0.5 second.

12.6.6 The emergency illumination level to be provided for roadway and walkway surfaces shall be a minimum average maintained value of 10 lx (1 fc) and, at any point, not less than 1 lx (0.1 fc), measured at the roadway and walkway surface.

12.6.6.1 A maximum-to-minimum illumination uniformity ratio of 40 to 1 shall not be exceeded.

12.6.7 Lighting shall be provided to highlight special emergency features including, but not limited to, fire alarm boxes, extinguishers and telephones, and special feature instructional signage.

12.6.8* Exit Signs.

12.6.8.1 Externally illuminated exit signs shall be illuminated by not less than 54 lx (5 fc) and employ a contrast ratio of not less than 0.5.

12.6.8.2 Internally illuminated exit signs shall produce a minimum luminance of 8.6 cd/m^2 (2.5 fl).

12.7* Security Plan. A security plan for the protection of the electrical supply substation to the facility shall be developed by the agency.

N **12.8 Wayfinding Lighting.**

N **12.8.1** Where provided, wayfinding lighting shall comply with 12.8.1.1 through 12.8.1.4.

N **12.8.1.1** Wayfinding lighting systems shall be installed and maintained in accordance with *NFPA 70*, NFPA 110, and NFPA 111.

N **12.8.1.2** Wayfinding lighting shall be powered by an emergency power supply.

N **12.8.1.3** There shall be no interruption of wayfinding lighting for greater than 0.5 seconds.

N **12.8.1.4** The wayfinding lighting systems shall be activated as a part of the coordinated operation of the tunnel emergency systems.

Chapter 13 Emergency Response

13.1 General. The agency that is responsible for the safe and efficient operation of the facility shall anticipate and plan for emergencies that can have an impact on the facility. Emergency operations planning input shall be solicited from the operators and emergency response agencies during the planning, design, and construction phases of the facility.

13.2* Emergency Incidents. The following typical incidents shall be considered during the development of facility emergency response plans:

(1) Fire or a smoke condition in one or more vehicles or in the facility
(2) Fire or a smoke condition adjoining or adjacent to the facility
(3) Collision involving one or more vehicles
(4) Loss of electric power that results in loss of illumination, ventilation, or other life safety systems
(5) Rescue and evacuation of motorists under adverse conditions
(6) Disabled vehicles
(7) Flooding of a travel way or an evacuation route
(8) Seepage and spillage of flammable, toxic, or irritating vapors and gases
(9) Multiple casualty incidents
(10) Damage to structures from impact and heat exposure
(11) Serious vandalism or other criminal acts, such as bomb threats and terrorism
(12) First aid or medical attention for motorists
(13) Extreme weather conditions, such as heavy snow, rain, high winds, high heat, low temperatures, or sleet and ice, that cause disruption of operation
(14) Earthquake
(15) Hazardous materials accidentally or intentionally being released into the tunnel

Δ **13.3* Emergency Response Plan.** An emergency response plan shall be submitted for acceptance and approval by the authority having jurisdiction (AHJ) and shall include, as a minimum, the following:

(1) Name of plan and the specific facility(ies) the plan covers
(2) Name of responsible agency
(3) Names of responsible individuals
(4) Dates adopted, reviewed, and revised
(5) Policy, purpose, scope, and definitions
(6) Participating agencies, senior officials, and signatures of executives authorized to sign for each agency
(7) Safety during emergency operations
(8) Purpose and operation of operations control center (OCC) and alternative location(s) as applicable:
    (a) Procedure for staffing the backup location(s) shall be specified.
    (b) Procedure to control risk while the OCC does not have staff until the backup facility can take over shall be specified.
(9) Purpose and operation of command post and auxiliary command post
(10) Communications (e.g., radio, telephone, messenger service) available at central supervising station and command post; efficient operation of these facilities
(11) Fire detection, fire protection, and fire-extinguishing equipment; access/egress and ventilation facilities available; details of the type, amount, location, and method of ventilation
(12)* Procedures for single or multiple concurrent fire emergencies, including a list of the various types of fire emergencies, the agency in command, and the procedures to follow.
(13) Maps and plans of the roadway system, including all local streets
(14) Any additional information that the participating agencies want to include
(15) Emergency response plan that recognizes the need to assist people who are unable to self-rescue with established, specific response procedures
(16) Emergency operational procedures developed based on the design
(17) Emergency response plan that includes traffic control procedures to regulate traffic during an emergency that can affect operation of the facility
(18)* Emergency response plan that considers degraded modes of operation as identified in NFPA 3 and NFPA 4, as applicable.
(19) Emergency response plan for tunnel facilities that anticipates elevated background noise levels within the facility resulting from the operation of emergency systems during various types of incidents, and provides specific guidance for emergency responders as to what noise levels to expect.

13.3.1 The emergency response plan shall clearly identify the authority or participating agency that is in command and responsible for supervision, correction, or alleviation of the emergency.

13.3.2 The emergency response plan shall include emergency response procedures, precautions, and training requirements for incidents involving alternative fuel vehicles. *(See Annex G.)*

13.4* Participating Agencies. Participating agencies and organizations that shall be considered to coordinate and assist, depending on the nature of the emergency, shall include the following:

(1) Ambulance service
(2) Building department
(3) Fire department (brigade)
(4) Medical service
(5) Police department
(6) Public works (e.g., bridges, streets, sewers)
(7) Sanitation department
(8) Utility companies (e.g., gas, electric, telephone, steam)
(9) Water supply
(10) Local transportation companies
(11) Private industry with heavy construction equipment available
(12) Land management agencies
(13) Towing companies
(14) Highway operators (e.g., departments of transportation)
(15) U.S. Coast Guard
(16) Military
(17) Federal Aviation Administration (FAA)

13.5* Operations Control Center (OCC). Subsections 13.5.1 through 13.5.8 shall apply where the facility has an OCC for the operation and supervision of the facility.

13.5.1 The OCC shall be staffed by qualified, trained personnel and shall be provided with the essential apparatus and equipment to communicate with, supervise, and coordinate all personnel in accordance with Chapter 26 of *NFPA 72*.

Δ **13.5.2*** The OCC shall serve as a supervising station to allow direct and indirect receipt of alarms.

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13.5.3 The OCC shall provide the capability to communicate rapidly with participating agencies.

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13.5.4 Equipment shall be available and shall be used for recording radio and telephone communications and CCTV transmissions during an emergency.

13.5.5 OCC personnel shall be thoroughly familiar with the emergency response plan and shall be trained to implement the plan.

Δ **13.5.6** Alternate location(s) shall be provided in the event the OCC is out of service for any reason and shall be equipped or have equipment readily available to function as required and have all necessary documents, records, and procedures available to duplicate the functions of the primary OCC.

13.5.7 The OCC shall be located in an area that is separated from other occupancies by construction that has a 2-hour fire resistance rating.

13.5.8 The OCC shall be protected by fire detection, fire protection, and fire-extinguishing equipment to provide early detection and suppression of fire in the OCC.

13.6 Liaisons.

13.6.1 An up-to-date list of all liaison personnel from participating agencies shall be maintained by the operating agency and shall be part of the emergency procedure plan.

13.6.2 The list of liaison personnel shall include the full name, title, agency affiliation, business telephone number(s), and home telephone number of the primary liaison, as well as an alternate liaison.

13.6.3 The liaison personnel list shall be reviewed at least once every 3 months to verify that the list is current.

13.7* Emergency. Emergency incidents shall be managed in accordance with NFPA 1561 or other equivalent internationally recognized standard.

13.8* Training, Exercises, Drills, and Critiques.

13.8.1 Operating agency and participating agency personnel shall be trained to function efficiently during an emergency.

13.8.2 Qualified personnel shall be thoroughly trained in all aspects of the emergency response plan, including operation of mechanical, electrical, and fire-life safety systems.

13.8.3* To optimize the emergency response plan, comprehensive training programs shall be conducted for all personnel and agencies that are expected to participate in emergencies.

13.8.4 Exercises and drills shall be conducted at least twice a year to prepare the operating agency and participating personnel for emergencies.

13.8.4.1 The AHJ shall approve the scope and content of the drill for meeting the intent of 13.8.4.

13.8.5 Critiques shall be held after exercises, drills, and actual emergencies.

13.8.6 Limited Access Highways.

13.8.6.1 Contacts shall be made with roadside businesses and responsible persons who live along limited access highways to elicit their cooperation in reporting fires and other emergencies.

13.8.6.2 The objective of such contacts shall be to establish a positive system for reporting emergencies.

13.8.6.3 Those who agree to participate in the system shall be provided with specific information on the procedures for reporting and a means for determining and reporting the location of the emergency as precisely as possible.

13.9 Records. Written records and telephone, radio, and CCTV recordings shall be kept at the central supervisory station (CSS), and written records shall be kept at the command post and auxiliary command post(s) during fire emergencies, exercises, and drills.

13.9.1 Revisions. Emergency response plan, documents, software, and other forms of records that have data that expire and/or may change and be needed for emergency management by the OCC or emergency responders shall be revised on a scheduled and timely basis, and as part of drills and exercises, but not less than annually.

13.9.1.1 Information that is critical to the success of fire-life safety emergency management, such as responsible individuals and contact personnel, shall be completed as the information changes.

Chapter 14 Regulated and Unregulated Cargoes

14.1 General.

14.1.1* The authority having jurisdiction (AHJ) shall adopt rules and regulations that apply to the transportation of regulated and unregulated cargoes.

14.1.2 Design and planning of the facility shall address the potential risk presented by regulated and unregulated cargoes as permitted by 14.1.1.

14.1.3* Development of such regulations as permitted by 14.1.1 shall address the following:

(1) Population density
(2) Type of highway
(3) Types and quantities of hazardous materials
(4) Emergency response capabilities
(5) Results of consultation with affected persons
(6) Exposure and other risk factors
(7) Terrain considerations
(8) Continuity of routes
(9) Alternative routes
(10) Effects on commerce
(11) Delays in transportation
(12) Climatic conditions
(13) Congestion and accident history

Chapter 15 Periodic Testing

Δ **15.1* General.**

15.1.1 Fire protection, life safety, emergency ventilation, communication, traffic control, and electrical systems shall be inspected and tested for operational readiness and performance in accordance with the frequency requirements of the applicable NFPA standards or in accordance with 15.1.2.

15.1.2 Integrated and/or interconnected fire protection, life safety, and emergency systems shall be inspected and tested for operational readiness and performance in accordance with the frequency requirements established by the basis of design or intervals not to exceed five years.

15.1.3 An inspection and repair program shall be kept in force to monitor and maintain the passive fire protection and fire separation elements of the facility.

Annex A Explanatory Material

Annex A is not a part of the requirements of this NFPA document but is included for informational purposes only. This annex contains explanatory material, numbered to correspond with the applicable text paragraphs.

A.1.3.1 The requirements of this standard reflect the practices and the state of the art prevalent at the time this standard was issued.

A.1.3.2 Where an extension is being considered for an existing road tunnel, the engineering analysis, as outlined in 4.3.1, should utilize the total extended length (i.e., existing tunnel length plus extension length) to determine the level of fire protection required by this standard.

A.1.6.1 SI units have been converted by multiplying the U.S. unit value by the conversion factor and rounding the result to the appropriate number of significant digits *(see Table A.1.6.1)*. See IEEE/ANSI SI 10, *Standard for the Use of the International System of Units (SI): The Modern Metric System.*

A.3.2.1 Approved. The National Fire Protection Association does not approve, inspect, or certify any installations, procedures, equipment, or materials; nor does it approve or evaluate testing laboratories. In determining the acceptability of installations, procedures, equipment, or materials, the AHJ may base acceptance on compliance with NFPA or other appropriate

Δ **Table A.1.6.1 Conversion Factors**

U.S. Units	SI Conversions
1 inch (in.)	25.4 millimeters (mm)
1 foot (ft)	0.3048006 meter (m)
1 square foot (ft^2)	0.09290304 square meter (m^2)
1 foot per minute (fpm)	0.00508 meter per second (m/sec)
1 foot per second squared (ft/sec^2)	0.3048 meter per second squared (m/sec^2)
1 footlambert (ft)	3.415457 candela/square meter (cd/m^2)
1 cubic foot per minute (ft^3/min)	0.000471947 cubic meter per second (m^3/sec)
1 gallon per minute (gpm)	0.06309020 liter per second (L/sec)
1 pound (lb)	0.45359237 kilogram (kg)
1 pound per cubic foot (lb/ft^3)	16.01846 kilograms per cubic meter (kg/m^3)
1 inch water gauge (in. wg)	0.249089 kilopascal (kPa)
1 pound per square inch (psi)	6.894757 kilopascals (kPa)
1 degree Fahrenheit (°F)	(°F - 32)/1.8 degrees Celsius (°C)
1 degree Rankine (°R)	1/1.8 Kelvin (K)
1 Btu per second (Btu/sec)	1055.05 watts (W)
1 Btu per pound degree Rankine (Btu/lb°R)	4.1868 joules per kilogram Kelvin (J/kg K)
1 footcandle (fc)	10.76391 lux (lx)
1 pound-force (lbf)	4.448222 newtons (N)
1 gallon (gal)	3.785411784 liters (L)
1 cubic foot per minute per lane foot ($ft^3/min{\cdot}lf$)	0.00155 cubic meters per second per lane meter ($m^3/sec{\cdot}lm$)
1 Btu per hour square foot ($Btu/hr{\cdot}ft^2$)	3.154591 watts per square meter (W/m^2)

standards. In the absence of such standards, said authority may require evidence of proper installation, procedure, or use. The AHJ may also refer to the listings or labeling practices of an organization that is concerned with product evaluations and is thus in a position to determine compliance with appropriate standards for the current production of listed items.

A.3.2.2 Authority Having Jurisdiction (AHJ). The phrase "authority having jurisdiction," or its acronym AHJ, is used in NFPA documents in a broad manner, since jurisdictions and approval agencies vary, as do their responsibilities. Where public safety is primary, the authority having jurisdiction may be a federal, state, local, or other regional department or individual such as a fire chief; fire marshal; chief of a fire prevention bureau, labor department, or health department; building official; electrical inspector; or others having statutory authority. For insurance purposes, an insurance inspection department, rating bureau, or other insurance company representative may be the authority having jurisdiction. In many circumstances, the property owner or his or her designated agent assumes the role of the authority having jurisdiction; at government installations, the commanding officer or departmental official may be the authority having jurisdiction.

A.3.2.4 Listed. The means for identifying listed equipment may vary for each organization concerned with product evaluation; some organizations do not recognize equipment as listed unless it is also labeled. The AHJ should utilize the system employed by the listing organization to identify a listed product.

A.3.3.5 Backlayering. See Figure A.3.3.5(a) through Figure A.3.3.5(c).

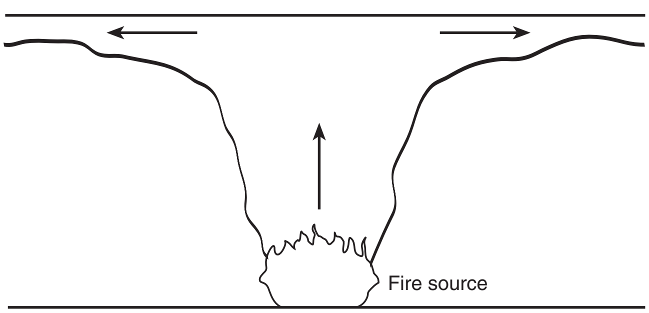
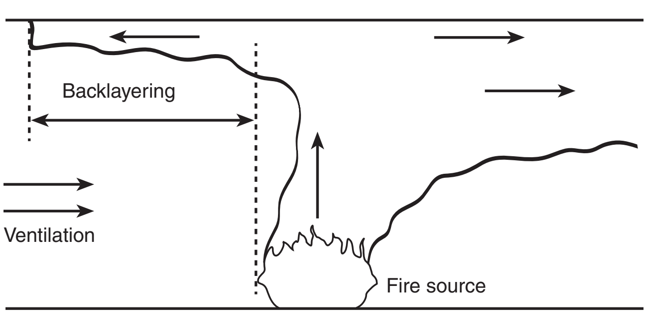


FIGURE A.3.3.5(a) Tunnel Fire Without Ventilation and Zero Percent Grade.



Δ FIGURE A.3.3.5(b) Insufficiently Ventilated Tunnel Fire Resulting in Backlayering.

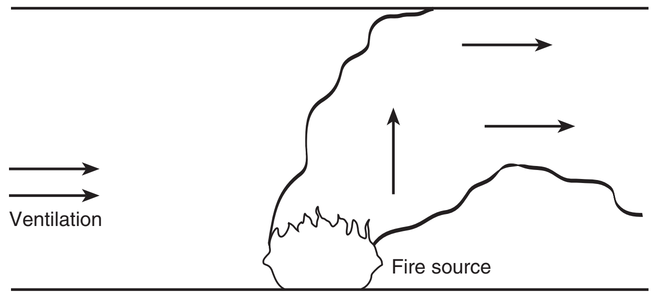


FIGURE A.3.3.5(c) Tunnel Fire Sufficiently Ventilated to Prevent Backlayering.

A.3.3.6 Basis of Design (BOD). The BOD is normally used to assist the commissioning authority and the AHJ in the plan review, inspection, and acceptance process.

A.3.3.8 Building. The term should be interpreted as if followed by the words "or portions thereof."

N **A.3.3.18 Design Fire Scenario.** A design fire scenario is selected for design inclusive of the conditions that define the fire development parameters, including the growth of fire, and describes factors such as ventilation conditions, ignition sources, arrangement and quantity of combustible materials, and fire load, that account for the effects of fire protection and life safety systems.

A.3.3.21 Emergency Communications. Emergency communications, where required, should be by the installation of outdoor-type telephone boxes, coded alarm telegraph stations, radio transmitters, or other approved devices *(see Section 4.5)*.

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N **A.3.3.30 Fire Growth Rate.** The fire growth rate is ordinarily expressed as Btu/sec^2 or MW/min.

N **A.3.3.31 Fire Risk Assessment.** Other documents might use other terms, such as fire risk analysis, fire hazard, hazard analysis, or fire hazard analysis assessment.

A.3.3.33 Fixed Water-Based Fire-Fighting System. This term includes sprinkler systems, water spray systems, and water mist systems.

N **A.3.3.34 Heat Release Rate.** The heat release rate of a fuel is related to its chemistry, physical form, and availability of oxidant and is ordinarily expressed as British thermal units per second (Btu/sec) or megawatts (MW).

A.3.3.35.1 Depressed Highway. See Figure A.3.3.35.1.

A.3.3.38 Incident Commander (IC). For additional information on traffic incident management, see the Federal Highway Administration website: http://ops.fhwa.dot.gov/eto_tim_pse/about/tim.htm.

A.3.3.39 Length of Bridge or Elevated Highway. Definitions associated with length of bridge or elevated highway include the following:

(1) Abutment. A retaining wall supporting the ends of the bridge or elevated highway.
(2) Approach. The part of the bridge that carries traffic from the land to the main parts of the bridge or elevated highway that does not meet the definition of a bridge or elevated highway.

FIGURE A.3.3.35.1 Depressed Highway.

(3) Bearing. A device at the ends of beams that is placed on top of a pier or abutment. The ends of the beam rest on the bearing.

A.3.3.44 Noncombustible Material. Standards other than ASTM E136, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C*, exist that are used to assess noncombustibility of materials. They include: ASTM E2652, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C with a Cone-Shaped Airflow Stabilizer*; ISO 1182, *Reaction to fire tests for products — Non-combustibility test*; and BS 476-4, *Fire tests on building materials and structures, Non-combustibility test for materials*.

A.3.3.47 Point of Safety. The egress population to be served should be determined by an engineering analysis.

A.3.3.60.1 Air-Right Structure. See Figure A.3.3.60.1.

A.4.1 Fire protection for limited access highways, road tunnels, and roadways beneath air-right structures and on bridges and elevated highways can be achieved through a combination of facility design, operating equipment, hardware, software, subsystems, and procedures that are integrated to provide requirements for the protection of life and property from the effects of fire.

A.4.2.1.1 Tunnel boring machine (TBM) cooling water can be used for the standpipe line, provided this line is always charged and functional and the pressures needed for standpipe outlets do not exceed pressure limits of the TBM. Restricting pressure can be achieved by use of a double backflow preventer.

A.4.3.1 The engineering analysis should be used to guide the decision process by the stakeholders and the AHJ for implementation of specific fire protection and life safety requirements.

The engineering analysis might, for some facilities, involve conducting a fire risk assessment that identifies the potential fire hazards and the consequential risks imposed by those hazards on the facility and its occupants. A fire risk assessment should be conducted as an adjunct to, and not a substitute for, qualified professional judgment. The content and the results of the fire risk assessment can be included in the emergency response plan documentation submitted to the AHJ. A fire risk assessment can also include a quantification of risks that can be used to inform a performance-based approach to safety.

In some circumstances, it might be appropriate to use a fire risk assessment to inform aspects of the design of the facility. Care should be taken to ensure that any such use of fire risk assessment is justified and robust.

FIGURE A.3.3.60.1 Air-Right Structure.

Where a fire risk assessment is used, risk acceptance criteria should be used. Risk acceptance criteria can be categorized as either "absolute" or "comparative." Absolute risk acceptance criteria should be generally specified on a case-by-case basis by relevant authorities or predetermined by regulation, while comparative risk acceptance criteria should demonstrate that the proposed facility design provides a level of risk equivalent to or better than a reference facility.

Guidance and background documentation for risk assessment can be found in the following documents:

(1) Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network
(2) OECD/PIARC QRA Model (http://www.piarc.org/en/knowledge-base/road-tunnels/gram_software/)
(3) NFPA 550, *Guide to the Fire Safety Concepts Tree*
(4) NFPA 551, *Guide for the Evaluation of Fire Risk Assessments*
(5) PIARC 2012, *Current Practice for Risk Evaluation for Road Tunnels*
(6) Ferkl, L. and A. Dix, "Risk Analysis: From the Garden of Eden to its Seven Most Deadly Sins"

A.4.3.2 Fire protection, life safety, or emergency systems are comprised of interdependent mechanical, electrical, communications, control, fire protection, structural, architectural, and other elements, all of which must function as a system to achieve the designed result. It is critical that all primary and supporting elements are protected to produce a similar level of combined system reliability for the design incident exposure.

This does not preclude loss of elements that are compensated for in the design.

A.4.3.3 Limited access highways can include other facilities covered by this standard.

A.4.3.5 The majority of depressed highways are associated with road tunnels that serve as connecting sections or open approaches.

A.4.3.6 Smoke and heated gases from a fire that do not readily disperse can seriously impede emergency response operations.

A.4.3.7 Smoke dispersion during a roadway fire emergency is similar to that during a fire in a road tunnel.

Fire protection for structures built over roadways are not covered by this standard, except for the separation between the air-right structure and the roadway beneath the air-right structure. However, fire protection and fire-life safety problems are complicated by limited access, by traffic congestion, and by any fire situation on the roadway that is located below or adjacent to the building.

A.4.3.8 Protection of related ancillary facilities such as service areas, rest areas, toll booths and plazas, pump stations and substations, and buildings used for administration, law enforcement, and maintenance presents problems that basically do not differ from fire protection problems for all buildings. However, special consideration should be given to the fact that where located on, or adjacent to, limited access highways, such buildings can be located in isolated areas. *(See NFPA 30 and NFPA 30A.)*

A.4.4.1 Emergency traffic control procedures can include vacating the incident travel lane, closing all or a portion of the roadway to traffic, or other methods approved by the AHJ.

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Δ **A.4.8** The provisions of 4.8 do not require inherently noncombustible materials to be tested in order to be classified as noncombustible materials.

Δ **A.4.8(1)** Examples of such materials include steel, concrete, masonry, and glass.

A.5.3 Recommendations regarding suitable fire apparatus for limited access highways can be found in Annex K.

A.5.5 As reported in "Incident Management Performance Measures" from the Texas Transportation Institute, the level of incident management and detection varies considerably from location to location. Many locations in the United States use motorist assistance patrols or service patrols that roam the freeways looking for incidents and providing necessary assistance to clear stalled or disabled vehicles off the roadway. Other locations have built a complex traffic control system that uses video surveillance cameras and automatic incident detection systems to monitor the status of the freeway and detect potential problem situations.

A.5.6 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 (1000 ft). The minimum required water supply for fire hydrants should not be less than 3780 L/min (1000 gpm) at 1.4 bar (20 psi) from each of two hydrants flowing simultaneously.

A.6.1 Guidelines regarding suitable fire apparatus for bridges and elevated highways can be found in Annex K.

A.6.2 Bridge or elevated highway approaches, on soil embankment fills or soil fills retained by retaining walls, with limited access, can be treated similar to a bridge or elevated highway as defined in this standard, at the discretion of the AHJ based on a risk assessment.

A.6.2.2 In assessing whether a bridge or elevated highway not fully enclosed should be defined as a tunnel, the AHJ should be guided by comparing the bridge or elevated highway not fully enclosed with a hypothetical tunnel that is otherwise equivalent to a bridge or elevated highway not fully enclosed.

If the bridge or elevated highway not fully enclosed is assessed to be similar to that of the hypothetical equivalent tunnel, then the bridge or elevated highway not fully enclosed should be defined as a tunnel and categorized in accordance with Section 7.2.

A.6.3.1 Preventing progressive structural collapse or collapse of primary structural elements should include analysis of the following effects of the fire:

(1) Loss of strength
(2) Loss of stiffness, causing plastic deformations
(3) Loss of durability due to cracking, which could lead to structural collapse (taking into account that some cracking, both during and after a fire, can occur at the nonvisible external perimeter of the structure that cannot be detected or repaired)
(4) Progressive fire-induced concrete spalling

A.6.3.2 The design fire scenarios to be used in the engineering analysis should include the following:

(1) Location A: Fire source centered at mid-span under the bridge deck spanning traffic below, both longitudinally and transversely
(2) Location B: Fire source centered at mid-span under the bridge deck spanning traffic below longitudinally, but transversely offset to be outside of an exterior girder
(3) Location C: Fire source transversely centered under the bridge but longitudinally offset close to the pier at the end of the span over traffic below
(4) Location D: Spill fire source on the bridge superstructure deck, with the spilled product entering the bridge drainage system
(5) Location E: Other locations based on engineering judgment and evaluation

Suggested design fire scenarios considered within the engineering analysis should include the following:

(1) For bridges spanning moving traffic, the design fire scenario typically includes a heavy goods truck.
(2) For a bridge spanning a freeway or interstate highway, the design fire scenario typically includes a flammable/combustible liquid tanker.

Refer to Table A.11.4.1.

Additional information for engineering evaluation is in *NCHRP Project 12-85: Highway Bridge Fire Hazard Assessment — Guide Specification for Fire Damage Evaluation in Steel Bridges.* This guide specification is intended to assist engineers with evaluation of highway bridge structures following fire events. This document discusses the fact that the majority of bridges in the United States consist of steel or concrete beams with concrete decks.

Additional information for engineering evaluation is in a graduate thesis prepared by Michael Davidson from Western Kentucky University, *Assessment of Passive Fire Protection on Steel-Girder Bridges*. This document suggests fire-induced bridge collapses are perpetuated by the general lack of installed fire protection systems.

A.6.6.1 Where a horizontal standpipe is required on a bridge or elevated highway under this standard, a vertical standpipe riser and fire department connection can be used to supply the standpipe from above or below. Where a horizontal standpipe system is required under Chapter 6, it should extend the full length of the bridge or elevated highway.

A.6.6.3 Where a municipal or privately owned waterworks system is available, consideration should be given to providing fire hydrants along bridges and elevated highways at spacing not to exceed 305 m (1000 ft). The minimum required water supply for fire hydrants should not be less than 3780 L/min (1000 gpm) at 1.4 bar (20 psi) from each of two hydrants flowing simultaneously.

A.7.1 Chapter 7 also covers requirements, where appropriate, for the fire protection and fire-life safety of depressed highways.

Δ **A.7.1.1** Additional information for engineering analysis can be found in *NCHRP Synthesis 415: Design Fires in Road Tunnels*. The document is primarily a literature review and includes chapters with the following titles: Tunnel Safety Projects, Tenable Environment, Significant Fire Incidents in Road Tunnels, Combined Use Roadways, Fire Tests, Analytical Fire Modeling, Design for Tunnel Fires, Compilations of Design Guidance, Standards and Regulations, Design Fire Scenario for Fire Modeling, Fixed Water-Based Fire Suppression and Its Impact on Tunnel Fires, Effects of Various Ventilation Conditions, Tunnel Geometry, and Structural and Non-Structural Tunnel Components.

A second source of tunnel fire characteristics is available in the PIARC report, *Design Fire Characteristics for Road Tunnels*. This document discusses tunnel fires, other publications, and smoke management implications, and has appendix language relative to practices adopted in other countries, fire tests, and real fire experiences.

Chapter 88, “Fires in Vehicle Tunnels” of the *SFPE Handbook of Fire Protection Engineering*, 5th edition, reviews published experimental research related to design fires for vehicle tunnels.

A.7.1.2 Passive fire protection is designed to reduce the heat flux to the tunnel wall. This reduction in heat losses to the tunnel wall increases the load on the tunnel ventilation system and should be considered in its design. Fixed water-based fire-fighting systems reduce the heat release rate, and this should be considered in the design of the tunnel ventilation system.

A.7.2 The categorizing of road tunnels is also influenced by their level of traffic congestion as evidenced by the tunnel’s peak hourly traffic count, as shown in Figure A.7.2. These minimum requirements, which are fully described within this standard, are summarized in Table A.7.2, as a reference guide to assist in the search for requirements listed elsewhere in this standard.

A.7.2.1 In assessing whether a facility not fully enclosed should be defined as a tunnel, the AHJ should be guided by comparing the facility not fully enclosed with a hypothetical tunnel that is otherwise equivalent to a facility not fully enclosed.

If the facility not fully enclosed is assessed to be similar to that of the hypothetical equivalent tunnel, then the facility not fully enclosed should be defined as a tunnel and categorized in accordance with Section 7.2.

A.7.3.1 Primary structural elements that should be considered would be constructed, for example, out of concrete, steel, masonry, or cast-iron.

Preventing progressive structural collapse and mitigation of structural damage should include analyses of the following effects of the fire on the primary structural elements:

(1) Loss of strength causing failure
(2) Loss of stiffness causing plastic deformations
(3) Loss of concrete durability due to cracking, which could lead to structural collapse (taking into account that some cracking, both during and after a fire, can occur at the non-visible, external perimeter of the structure, that cannot be detected or repaired)
(4) Specifically for concrete: fire-induced spalling, which could lead to structural collapse

Δ **A.7.3.2** Any passive fire protection material should satisfy the following performance criteria:

(1) Be resistant to freezing and thawing and follow STUVA Guidelines; BS EN 12467, *Fibre-cement flat sheets. Product specification and test methods*; or ASTM C666, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*
(2) Withstand dynamic suction and pressure loads; 3 kPa (12 in. w.g.) to 5 kPa (20 in. w.g.) depending on traffic type, cross section, and speed limits; amount of cycles to be determined based on traffic volume
(3) Withstand both hot and cold thermal shock from fire exposure and hose streams
(4) Meet all applicable health and safety standards
(5) Not itself become a hazard during a fire
(6) Be resistant to water ingress; follow BS EN 492, *Fibre-cement slates and fittings. Product specification and test methods*

The time-temperature development for the RWS curve is shown in Table A.7.3.2(a) and in Figure A.7.3.2(a). Other internationally recognized standardized time-temperature curves are shown in Figure A.7.3.2(c).

An engineering analysis for the purposes of determining the appropriate time-temperature curve should consider the following:

(1) Tunnel geometry
(2) Types of vehicles anticipated
(3) Types of cargoes
(4) Expected traffic conditions
(5) Fire mitigation measure(s)
(6) Reliability and availability of fire mitigation measure(s)

Δ Table A.7.2 Minimum Road Tunnel Fire Protection Reference Guide

		Road Tunnel Categories				
Fire Protection Systems	**NFPA 502 Sections**	**X** *[See 7.2(1).]*	**A** *[See 7.2(2).]*	**B** *[See 7.2(3).]*	**C** *[See 7.2(4).]*	**D** *[See 7.2(5).]*
Engineering Analysis						
Engineering analysis	4.3.1	MR	MR	MR	MR	MR
Fire Protection of Structural Elements[a]						
Fire protection of structural elements	7.3	MR	MR	MR	MR	MR
Fire Detection						
Detection, identification, and location of fire in tunnel	7.4	—	—	MR	MR	MR
CCTV systems[b]	7.4.3	—	—	CMR	CMR	CMR
Automatic fire detection systems[b]	7.4.6.7	—	—	CMR	CMR	CMR
Fire alarm control panel	7.4.7	—	—	MR	MR	MR
Emergency Communications Systems[c]						
Emergency communications systems	4.5/7.5	CMR	CMR	CMR	CMR	CMR
Traffic Control						
Stop traffic approaching tunnel portal	7.6.1	MR	MR	MR	MR	MR
Stop traffic from entering tunnel's direct approaches	7.6.2	—	—	MR	MR	MR
Fire Protection						
Fire apparatus[d]	7.7	—	—	—	—	—
Fire standpipe	7.8/10.1	—	MR	MR	MR	MR
Water supply	7.8/10.2	—	MR	MR	MR	MR
Fire department connections	10.3	—	MR	MR	MR	MR
Hose connections	10.4	—	MR	MR	MR	MR
Fire pumps[e]	10.5	—	CMR	CMR	CMR	CMR
Portable fire extinguishers	7.9	—	—	MR	MR	MR
Fixed water-based fire-fighting systems[f]	7.10/9.0	—	—	—	CMR	CMR
Emergency ventilation system[g]	7.11/11.0	—	—	CMR	CMR	MR
Tunnel drainage system[h]	7.12	—	CMR	MR	MR	MR
Hydrocarbon detection[h]	7.12.7	—	CMR	MR	MR	MR
Flammable and combustible environmental hazards[i]	7.15	—	—	CMR	CMR	CMR
Means of Egress						
Emergency egress	7.16.1.1	—	—	MR	MR	MR
Exit identification	7.16.1.2	—	—	MR	MR	MR
Tenable environment	7.16.2	—	—	MR	MR	MR
Walking surface	7.16.4	—	—	MR	MR	MR
Emergency exit doors	7.16.5	—	—	MR	MR	MR
Emergency exits (includes cross-passageways)[j]	7.16.6	—	—	MR	MR	MR
Electrical Systems[k]						
General	12.1	—	CMR	MR	MR	MR
Emergency power	12.4	—	CMR	MR	MR	MR
Emergency lighting	12.6	—	CMR	MR	MR	MR
Exit signs	12.6.8	—	CMR	MR	MR	MR
Security plan	12.7	—	CMR	MR	MR	MR
Emergency Response Plan						
Emergency response plan	13.3	MR	MR	MR	MR	MR

MR: Mandatory requirement (3.3.42). CMR: Conditionally mandatory requirement (3.3.42.1).

Note: The purpose of Table A.7.2 is to provide guidance in locating minimum road tunnel fire protection requirements contained within this standard. If there is any conflict between the requirements defined in the standard text and this table, the standard text must always govern.

[a]Determination of requirements in accordance with Section 7.3.

[b]Determination of requirements in accordance with Section 7.4.

[c]Determination of requirements in accordance with Sections 4.5 and 7.5.

[d]Not mandatory to be at tunnel; however, they must be near to minimize response time.

[e]If required, must follow Section 10.5.

[f]If installed, must follow Section 7.10 and Chapter 9.

[g]Section 11.1 allows engineering analysis to determine requirements.

[h]If required, must follow Section 7.12.

[i]Determination of requirements in accordance with 7.16.2.

[j]Emergency exit spacing must be supported by an egress analysis in accordance with 7.16.6.

[k]If required, must follow Chapter 12.

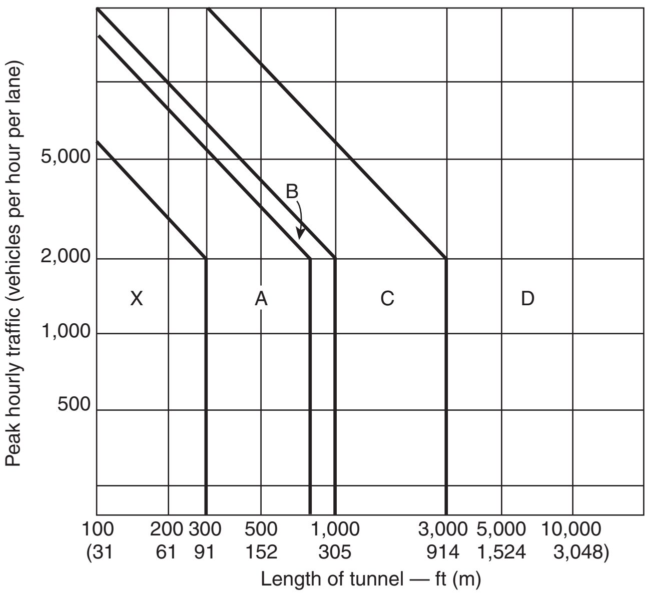


FIGURE A.7.2 Urban and Rural Tunnel Categories.

The RWS fire curve represents one of the standardized time-temperature curves, which was initially developed during extensive testing conducted by the Dutch Ministry of Transport (Rijkswaterstaat, RWS) in cooperation with the Netherlands Organization for Applied Scientific Research (TNO) in the late 1970s, and later proven in full-scale fire tests in the Runehamar tunnel tests in Norway in September 2003, conducted as part of the European Union (EU)–funded research project, Cost-Effective Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels (UPTUN), in association with SP Technical Research Institute of Sweden and the Norwegian Fire Research Laboratory (SINTEF/NBL).

As shown in Table A.7.3.2(b), four tests were carried out on fire loads of nonhazardous materials using timber or plastic, furniture, mattresses, and cardboard cartons containing plastic cups.

All tests produced time-temperature developments in line with the RWS curve as shown in Figure A.7.3.2(b).

All fires produced heat release rates of between 70 MW for cardboard cartons containing plastic cups and 203 MW for timber/plastic pallets.

Figure A.7.3.2(c) depicts the T1 fire test time-temperature development in comparison to various standardized time-temperature curves.

The RWS requirements are adopted internationally.

The level of fire resistance of structures and the emergency time/temperature certification of equipment should be proven by testing or reference to previous testing.

Fire test reports are based on the following requirements:

(1) Concrete slabs used for the application of passive fire protection materials for fire testing purposes have dimensions of at least 1400 mm × 1400 mm (55 in. × 55 in.) and a nominal thickness of 150 mm (6 in.).
(2) The exposed surface is approximately 1200 mm × 1200 mm (47 in. × 47 in.).

Table A.7.3.2(a) Furnace Temperatures

Time (min)	Temperature °C	Temperature °F
0	20	68
3	890	1634
5	1140	2084
10	1200	2192
30	1300	2372
60	1350	2462
90	1300	2372
120	1200	2192

(3) The passive fire protection material is fixed to the concrete slab using the same fixation material (anchors, wire mesh, etc.) as will be used during the actual installation in the tunnel.
(4) In the case of board protection, a minimum of one joint in between two panels should be created, to judge if any thermal leaks would occur in a real fire in the tunnel.
(5) In the case of spray materials, the number of applications (number of layers) should be registered when preparing the test specimen. This number of layers should be considered when the spray material is applied in a real tunnel.
(6) Temperatures are recorded by K-type thermocouples in the following locations:
    (a) At the interface between the concrete and the passive fire protection material
    (b) At the bottom of the reinforcement
    (c) On the nonexposed face of the concrete slab

    For an example test procedure to assess the spalling and the thermal protection of a concrete structure, see Efectis-R0695, “Fire Testing Procedure for Concrete Tunnel Linings.”

The installation of passive fire protection materials should be done with anchors having the following properties:

(1) The diameter should be limited to a maximum of 6 mm (¼ in.) to reduce the heat sink effect through the steel anchor into the concrete. Larger diameter anchors can create a spalling effect on the concrete.
(2) The use of high-grade stainless steel anchors is recommended.
(3) If necessary, a washer should be used to avoid a pull-through effect when the system is exposed to dynamic loads.
(4) The anchors should be suitable for use in the tension zone of concrete (cracked concrete).
(5) The anchors should be suitable for use under dynamic loads.

A.7.3.3(2) Fire-induced spalling is the result of a combination of rising pore pressures and thermal gradients in the concrete. At the front of heat penetration, a moisture clog (area with high pore pressure) develops inside the concrete. Part of the moisture is pushed further into the colder part of the concrete due to the pressure gradient at the back of the clog. If the heated surface is under additional compression due to a thermal gradient, pre-stressing, design load, or other factors, the complete heated surface can spall.

Δ **Table A.7.3.2(b) Fire Test Data**

Test	Time from Ignition to Peak HRR (min)	Linear Fire Growth Rate (MW/min) (R-Linear Regression Coefficient)	Peak HRR (MW)	Estimated HRR from Laboratory Tests (No Target / Inclusive Target) (MW)
1	18.5	20.1 (0.996)	201.9	186/217
2	14.3	26.3 (0.992)	156.6	167/195
3	10.4	16.4 (0.998)	118.6	—
4	7.4	16.9* (0.996)	66.4	79/95

* 5-66.4 MW

This type of spalling is especially likely to occur on structural members heated from more than one side, such as columns and beams. When moisture clogs are advancing into the concrete from all heated sides, at some point in time the moisture clogs will meet in the center of the cross-section, resulting in a sudden rise in pore pressure, which can cause large parts to spall.

Some factors that can influence concrete susceptibility, which are time frame, explosiveness, and progressiveness of the spalling, can include material properties, concrete mix, reinforcing, casting conditions, curing conditions, finishing methods, geometry, dimensions, moisture content, structural loading and supports, pre-stressing, and fire exposure.

A.7.4.3 The requirement in this clause for 24-hour supervision presumes that the supervision is effective for both the identification of an incident and for an effective incident response initiated by the supervising entity.

N **A.7.4.6** Additional information on automatic fire detection systems is provided in Annex M.

Δ **A.7.4.6.1** In road tunnels where 24-hour supervision is not provided, consideration should be given to integrating the required automatic fire detection with the operation of the traffic control system to alert motorists that there is a fire in the tunnel.

The activation of the fire detection system could activate those traffic control devices necessary to notify motorists of a fire in the tunnel, to stop approaching traffic from entering the tunnel, and notify motorists inside the tunnel that they are approaching the fire.

As a minimum, the traffic control devices that should be considered for integration with the fire alarm system include the variable message signs located on the approach roadways, at the tunnel entrance portal and inside the tunnels, and lane use signals at the portal and in the tunnel.

N **A.7.4.6.2** Signals can be used to automatically provide information to motorists on evacuation direction(s) with operator oversight. Without operator oversight, directional signals could place motorists in additional danger posed by other hazards or failure of the automatic systems to correctly identify the location of fire hazards.

A.7.4.6.7 Automatic fire detection systems should be able to detect a tunnel fire incident of 5 MW or less within 90 seconds or better in a testing environment of 3 m/sec (590 fpm) air velocity.

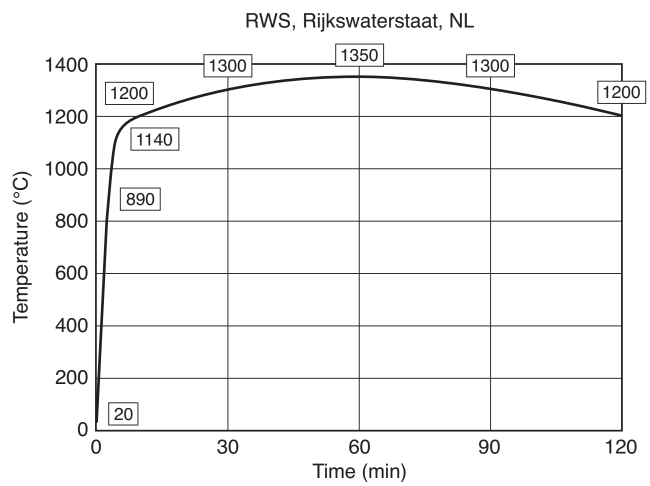


FIGURE A.7.3.2(a) RWS Time-Temperature Curve.

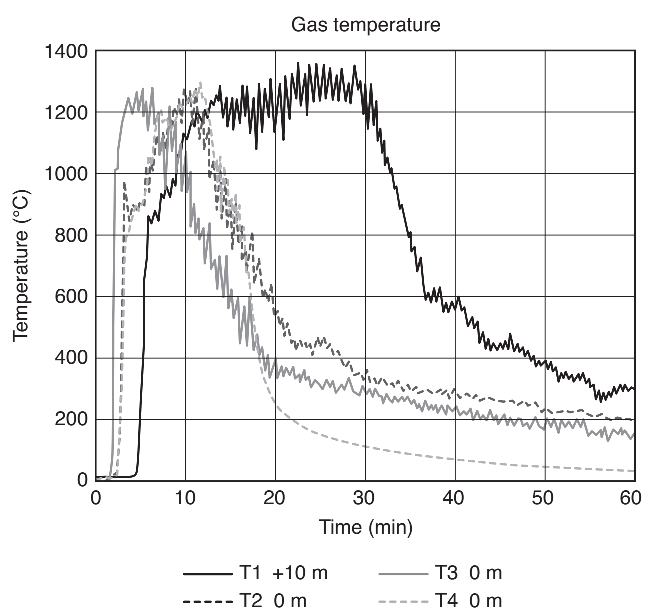
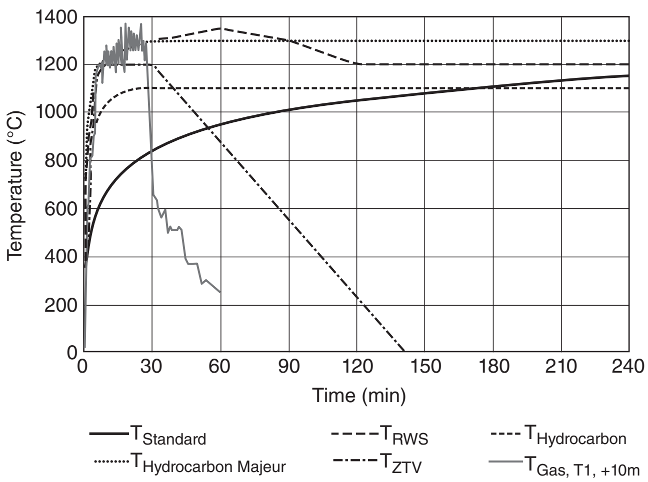


FIGURE A.7.3.2(b) Test Fire Curves.



Δ **FIGURE A.7.3.2(c) Various Standardized Time-Temperature Curves and Fire Test Time-Temperature Development.**

N **A.7.4.7** For facilities that utilize a supervisory control and data acquisition (SCADA) system to monitor and control facility sub-systems as part of an integrated emergency response system (i.e., ventilation, fire protection, traffic control, emergency communications systems, etc.), the fire alarm control panel (FACP) should interface with the SCADA system for the purpose of reporting alarm signals from the automatic fire detection system directly to the SCADA system. The number of data points exported from the FACP to the SCADA system should be sufficient to provide notifications, alarms, and status conditions to the SCADA system necessary to allow the initiation of an appropriate sub-system response by the SCADA system to the alarms and conditions received from the automatic fire detection system.

N **A.7.4.7.1** The monitoring and control of sub-systems can vary, depending on the level of supervision provided. For example, for tunnels without 24-hour supervision, the activation of sub-systems in response to a fire emergency can be directly initiated from the FACP, whereas for facilities where sub-systems are monitored and controlled through an approved SCADA system, the SCADA system is utilized to initiate sub-system activation.

A.7.5 Radio communications systems, such as highway advisory radio (HAR) and AM/FM commercial station overrides, can be provided to give motorists information regarding the nature of the emergency and the actions the motorist should take. All messaging systems should be capable of real-time composition. The communications system can also feature a selection of prerecorded messages for broadcasting by the emergency response authority. Areas of refuge or assembly, if available, should be provided with reliable two-way voice communications to the emergency response authority.

A.7.6.2(3) Consideration should be given to the various scenarios that affect flow from the tunnel and the various means to mitigate their impact. These means include the control of heat and smoke or the installation of fixed water-based fire-fighting systems.

N **A.7.7** Annex K provides additional information on fire apparatus for road tunnels.

A.7.8 Where a municipal or privately owned waterworks system is available, consideration should be given to providing fire hydrants along road tunnels at spacing not to exceed 305 m (1000 ft). The minimum required water supply for fire hydrants should not be less than 3780 L/min (1000 gpm) at 1.4 bar (20 psi) from each of two hydrants flowing simultaneously. This supports fire-fighting operations where it is necessary or desirable to position fire apparatus within the tunnel.

A.7.9 Consideration should be given to incorporating into the alarm system a means for detecting the removal of an extinguisher.

A.7.12 This section is not intended to apply to ground water or soil drainage systems that have no connection to the roadway drainage system and have no exposure to the environment in the tunnel.

A.7.12.1 This effluent can include water from tunnel-cleaning operations and water from incidental seepage, in addition to the water discharged from the fire protection system and liquids from accidental spills.

A.7.12.2 The road surface drain path is the route the liquid travels from the spill location to the drainage inlets along the road surface. By controlling the slope, drainage inlet spacing, and drainage system capacity, the exposed surface of liquid allowed to accumulate on the road surface between the spill location and the nearest drainage system inlet(s) can be reduced. This can reduce the exposure to other vehicles, tunnel systems, and the tunnel structures to fire if the liquid were to ignite.

A.7.12.4 Examples of combustible materials that should not be used in drainage systems include plastic pipes of any kind, including polyvinyl chloride (PVC), polybutylene or polyethylene, or fiberglass pipes.

A.7.12.5 If fixed fire water-based fire suppressions are installed, then consideration must also be given to the flows from those systems.

A.7.12.5.2 For tunnels that allow transport of bulk hazardous or flammable liquid cargo, the drainage system should consider the rate of flow that could result from the rupture of a bulk liquid transport tank. Where warranted by the traffic volume of bulk hazardous or flammable liquid carriers, consideration might include an overturned tanker involved in a collision with another tanker wherein two bulk liquid transport tanks could rupture simultaneously in a single event. Where bulk hazardous or flammable cargo is prohibited, then smaller flow rates might be expected from sources such as intermodal containers or fuel tanks for the vehicle(s).

N **A.7.13** Annex G provides additional information on alternative fuels.

A.7.14.1 Large flammable and combustible liquid fires in tunnels are typically oxygen-limited fires; however, another method to control the fire is to control the surface area of the pool spill by draining the liquid before the spill surface area grows to size. Controlling the surface area would reduce fire size, burn time, fire growth rate, and the consequent smoke propagation by reducing the burning area of the liquid, considering the following:

(1) A single large flammable/combustible liquid tanker is approximately 6661.4 imperial gallons (8000 U.S. gallons) from a single tank, or 13,332.8 imperial gallons

(16,000 U.S. gallons) from a combination truck and trailer tanker.

(2) The drainage and pool containment approach would normally be used for moderate-sized leaks up to approximately 250 gpm (which is roughly equivalent to a 3 in. pipe opening near the bottom of a gasoline tanker).

(3) For larger spills, that is, possibly several thousand gallons over a very short time frame, the drainage and pool containment system would need to include slope considerations and significantly large drainage capacity. This type of spill might occur from overturned tanker accidents that open a large hole or gash in the container wall.

(4) Design assumptions for the spill rate, quantity, and type of expected flammable liquid must be approved by the AHJ.

(5) Flammable and combustible liquid controls would need to be channeled through an approved "fire trap" arrangement in advance of any separation, and detention or diversion areas to prevent fire from propagating beyond the tunnel or to prevent the fire from propagating into the pump station wet wells located inside the tunnel.

(6) Oil/water separators allow control of most of the flammable/combustible liquids to be isolated from water, thereby reducing the quantity of flammable/combustible liquid needed to be managed.

(7) If flammable liquid detention is used, the detention capacity must be sized to accommodate all the flammable/combustible liquid entering the system. If adequate separation is not provided, the detention must be sized to include the flammable/combustible liquid as well as the other liquids, notably rain/snow, leaks, and fire suppression water from both handlines and the fixed water-based suppression system(s).

(8) If the flammable/combustible liquid is not detained, it should be diverted to a remote holding area with specific precautions to prevent ignition sources and environmental concerns. Size of remote areas would need to be proportionately larger if no separation is included.

(9) Pumps and other ancillary electrical equipment used to move the flammable and combustible liquid should conform to the requirements of the hazard classification.

(10) The engineering analysis should address potential blockage of one drainage inlet to the collection system by debris as a result of the incident.

A.7.15 There are a host of potential constructed and naturally occurring environmental sources of fire-life safety hazards external to road tunnels to be considered. Analysis, design, property acquisition, construction, operation, and maintenance for road tunnels should consider at a minimum the following:

(1) Existing, abandoned, and planned change in the risk profile from flammable and combustible material intrusion. This would include contaminated soils from past, present, or future leakage, and intrusion from other external sources.

(2) Intrusion of gases both naturally occurring, such as methane, and introduced, such as natural gas in pipelines. Several challenges arise with hazards emanating from abutting unrelated properties and facilities, either existing before the tunnel construction or with a potential to be constructed later. It is advised to include determination of existing or abandoned items such as storage and related piping in the planning phase with respect to tunnel routing and encumbrances on abutting properties. For example, NFPA 30 and NFPA 30A address requirements for flammable and combustible liquids storage tanks. The requirements for storage tanks and piping might not include consideration of the potential effects on a tunnel. It is unlikely third parties will consult the standard, be sensitive to the fire-life safety risks posed by their activities, or be sensitive to the special risks their activities pose.

A.7.16.1.1 Only the exit design and construction requirements from NFPA *101* should be applied to tunnels. It is not the intent of these requirements to apply the requirements for travel distances and accessible means of egress in NFPA *101* to road tunnels.

However, the protection of mobility-impaired individuals and their impact on the egress should be addressed as part of the emergency response plans in Chapter 13 and Annex E.

A.7.16.1.2 Consideration should be given to the height of the sign above the walking surface (e.g., raised walkway or curbed walkway) as it affects visibility during a fire emergency.

N **A.7.16.1.3** Wayfinding can include items such as specific markings along pathways, pathway lighting, and additional illumination.

The following references provide additional information on wayfinding:

(1) CIE 193, *Emergency Lighting in Road Tunnels*
(2) NCHRP 216: *Emergency Exit Signs and Marking Systems for Highway Tunnels*
(3) CETU Information Document, *Signalling and Support Measures for Self-Evacuation of Users from Road Tunnels*

A.7.16.2 The duration of the evacuation phase may be affected by travel distances to emergency exits. For additional information on tenable environments in road tunnels, see Annex B.

A.7.16.5.1 The opening of an emergency exit door should trigger an alarm.

A.7.16.5.4 Horizontal sliding doors have the advantage of opening in the event of large pressure differential impacts and are commonly used for both directions of exit travel.

A.7.16.5.5 There might not be readily available exit door assemblies that meet this requirement, which will therefore require adaptation of existing door assemblies, or design and construction of new door assemblies. These should be tested.

A.7.16.5.6 The air pressure on the doors can be due to one or more of the following reasons:

(1) Tunnel ventilation
(2) Pressure produced by pressurization fans
(3) Traffic dynamics under normal and emergency conditions
(4) Natural pressure difference in tunnels, especially those with a steep grade

Design of emergency exit doors should consider wear and maintenance. Emergency exit tunnel door openings should have no sill. Projections with a height of less than 40 mm (1.5 in.) are not considered to be door sills.

A.7.16.5.7 Air leakage should not exceed 0.15 m^3/sec (320 cfm) in the case of a pressure difference of 50 Pa (0.2 in. w.g.) in the direction of escape.

A.7.16.6.1 The primary purpose of emergency exits is to minimize exposure of the evacuating vehicle occupants to an untenable environment and to provide emergency response access and minimize response time.

A.7.16.6.2 The calculation of appropriate exit spacing should be the subject of emergency egress analysis. Independent of the results of such analysis, the distance between such exits should not be more than 300 m (1000 ft). Typically, for urban tunnels, such analysis has resulted in exit spacings of much shorter separations, both within the U.S. and internationally. There is not considered to be any "minimum" exit separation; however, most typical exit separations are between 30 m (100 ft) and 200 m (656 ft). Appropriate exit separation distances can only be determined by engineering analysis of emergency egress requirements.

"Types and classes of tunnels" refers to parameters such as structural type, number of bores, depth of cover, tunnel location, traffic mix, and so forth.

Δ **A.7.16.6.3** The maximum means of egress travel speed should be computed for reduced visibility due to a smoke-filled environment. The travel speed for such an environment is in the range of 0.5–1.5 m/sec (100–300 fpm) depending on visibility, illuminance, design of exit signs, and egress pathway.

A.7.16.6.3.1 The maximum travel distance should be computed as the distance to the next available exit as well as with consideration for the width of the roadway. Exit availability should consider exit capacity, obstructions due to traffic or incident conditions, and tenability.

N **A.7.16.6.4** Where cross-passages are used as an emergency exit, dividing walls between adjacent tunnels should comply with Section 7.3 and should be of a minimum 2-hour fire-rated construction.

N **A.7.16.6.6** If ventilation designs include smoke exiting portal(s), this might result in the egress pathway being in the smoke.

A.8.1 Air-right structures impose on the accessibility and operation of the roadway during emergency operations.

A.8.2.3 In assessing whether an air-right structure not fully enclosed should be defined as a tunnel, the AHJ should be guided by comparing the air-right structure not fully enclosed with a hypothetical tunnel that is otherwise equivalent to an air-right structure not fully enclosed.

If the air-right structure not fully enclosed is assessed to be similar to that of the hypothetical equivalent tunnel, then the air-right structure not fully enclosed should be defined as a tunnel and categorized in accordance with Section 7.2.

A.8.4.1.1 Acceptable risks could be modified by increasing fire resistance and/or installing a fixed water-based fire-fighting system.

A.8.9 Where a municipal or privately owned waterworks system is available, consideration should be given to providing fire hydrants along roadway beneath air-right structures at spacing not to exceed 305 m (1000 ft). The minimum required water supply for fire hydrants should not be less than 3780 L/min (1000 gpm) at 1.4 bar (20 psi) from each of two hydrants flowing simultaneously. This supports fire-fighting operations where it is necessary or desirable to position fire apparatus within the air-right structure.

A.9.1 For additional information on fixed water-based fire-fighting systems in road tunnels, see Annex E.

A.9.2.2 When determining how to incorporate a water-based fire-fighting system into the design of a tunnel, it is critical to explicitly determine the type of performance the water-based fire-fighting system is expected to provide. As part of this process, it is necessary to decide if the water-based fire-fighting system should improve tenability during the evacuation phase, improve tenability for fire fighters conducting manual fire-fighting activities, increase the effectiveness of the ventilation systems, or simply improve the fire resistance of the tunnel structure.

In general, the performance of water-based fire-fighting systems installed in transportation tunnels can be grouped into the four categories addressed in 9.2.2.1 through 9.2.2.4.

A.9.2.2.1 Fire suppression systems are designed to arrest the rate of fire growth and significantly reduce the energy output of the fire shortly after operation. Suppression mode systems are very suitable for improving the ability of first responders to engage in search and rescue as well as manual fire-fighting activities. Suppression systems, if operated early enough in the fire event, may improve the ability of and time available for tunnel occupants to evacuate.

A.9.2.2.2 Fire control systems are designed significantly to reduce or stop the rate of fire growth, but not necessarily to reduce the energy output of an established fire. Fire control water-based fire-fighting systems are most suitable for providing structural protection and, if operated early enough, may improve the ability of first responders to engage in manual fire fighting. They also provide additional time for tunnel evacuation depending upon the anticipated fire size at system activation.

A.9.2.2.3 Volume cooling systems are designed to reduce the temperature of heated products of combustion, and of systems and tunnel structure, but may not have any direct effect on fire size or fire growth rate. Volume cooling systems are most suitable for providing structural protection and improving the efficiency of ventilation systems, and may provide additional time for tunnel evacuation and first responder access depending upon anticipated fire size at system activation and fire growth rates.

A.9.2.2.4 Surface cooling systems are designed to provide cooling of specific objects or surfaces to improve the survivability of these objects. Surface cooling systems do not have any direct effect on fire size or fire growth rate. Surface cooling systems are most suitable for providing structural protection and extending the survival time for critical tunnel components. Surface cooling systems are not expected to improve egress time or tenability, and are exclusively intended for property protection.

A.9.4.2 Design of a fixed water-based fire-fighting system should consider any relevant available data resulting from full-scale tunnel fixed water-based fire-fighting tests of the type of systems being used. The fire scenario employed in the design process should use a representative fire curve for the type and use of the tunnel. The type, application rates, and coverage design of the fixed water-based fire-fighting system should be based on the combination of an engineering analysis, test results, and manufacturer installation guidelines in consultation with the AHJ. The design should be in accordance with applicable NFPA standards.

A.9.4.3 Listing or approval of individual components is required to ensure that standards of quality and performance are maintained. The intent of this requirement is not to mandate that system components be listed or approved for use in tunnels, but rather that they be listed for use as part of a water-based fire-fighting system. However, it should be noted that being listed or approved for use as a component in a water-based fire-fighting system does not guarantee that the component is suitable for use within the tunnel environment.

A.9.7.1 Transportation tunnels are highly integrated structures. The impact of water-based fire-fighting systems on life safety and the overall performance and behavior of critical tunnel systems must be evaluated as part of the tunnel design process.

A.10.1.5 Calculations, including transit and fill times, should be submitted to the AHJ to support this requirement.

Further assistance is provided in "A Basis for Determining Fill Times for Dry Fire Lines in Highway Tunnels," published by ASME.

A.10.4.2 If the hose connections are 83.8 m (275 ft) apart, some fire departments that carry hand hose lines that are less than 91.4 m (300 ft) in length cannot readily deploy hose and reach the fire through stopped vehicles without a delay to bring more hose. Where the fire department carries hand lines that are shorter than 91.4 m (300 ft), the AHJ can require closer spacing to avoid delay. Where possible, the hose connection should be placed adjacent to the exit if the exit will be used as a fire department access.

A.11.1 Tunnel ventilation systems that are installed in road tunnels are an important element of tunnel fire protection systems. Ventilation systems are installed in road tunnels to maintain an acceptable level of traffic-generated pollutants within the tunnel roadway.

Ventilation systems that are designed to control the contaminant levels within road tunnels (normal operations) can be configured several ways, employing either central fans or local fans.

A.11.1.1 For guidance on developing an appropriate engineering analysis, the user should reference the performance-based alternatives in NFPA *101*.

A.11.1.4 Consideration should be given to methods that will allow for early detection or indication of a fire to facilitate timely activation of emergency ventilation systems.

A.11.2 A description of the various ventilation configurations for normal operations is contained in Annex I.

Smoke control can be achieved either by capturing and removing the smoke through air ducts or by pushing it through the tunnel and out a portal. The approach used will depend on the type of ventilation systems elected and on the mode of traffic operation and the surrounding environment.

The Memorial Tunnel Fire Ventilation Test Program (MTFVTP), a full-scale test program, was conducted under the auspices of the United States Federal Highway Administration (FHWA), the Massachusetts Highway Department (MHD), and the American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE) to evaluate the effectiveness of various tunnel ventilation systems and ventilation airflow rates to control the smoke from a fire. The results of this program had an impact on the design criteria for road tunnel emergency ventilation. Information from the MTFVTP has been employed in the development of this standard. A description of the MTFVTP and its results are contained in Annex H.

A.11.2.4 In any tunnel configuration where other events can result in vehicles being stopped on both sides of a fire site the provisions of 11.2.3 should apply.

A.11.2.4(1)(a) Avoid disruption of the smoke layer by not producing velocities that are significantly greater than the critical calculated velocity. If the longitudinal air velocity in the tunnel is much greater than the critical velocity, the high flow rates could have the advantage of reducing temperature and decreasing toxicity in the tunnel. However, they will completely destroy the smoke stratification and might cause the fire to grow faster to a larger fire size. Furthermore, excessive longitudinal air velocity can lead to a faster fire spread among vehicles trapped in the tunnel.

Achieving a limitation of backlayering such that it does not extend beyond the untenable zone as determined in B.3(2) should be accepted as effectively preventing backlayering.

A.11.4 It has been recognized from experimental results that fixed water-based fire-fighting systems can be effective in limiting the spread of fire and thus controlling the fire size.

Δ **A.11.4.1** Experimental fire heat release rates (HRR) and representative HRR that correspond to various vehicle types are provided in Table A.11.4.1. Experimental HRR are given in the first and last columns, obtained from fire tests carried out in various full-scale tunnels or fire laboratories. The representative HRR given in the second column are suggested as typical peak HRR and time-to-peak HRR without fixed water-based fire-fighting systems (FFFS).

The design fire scenario should take into account project-specific factors and the presence of FFFs directly relating to the engineering objective to be achieved, and these can include the following:

(1) Tunnel geometry, including aspect ratio (height, width, and cross-sectional profile)
(2) Traffic- and vehicle-type characteristics such as percentage of heavy goods vehicles, fire load, fuel containment, fuel type, geometric configuration of the vehicle, body material type, existence of vehicle fire suppression system, and vehicle mix
(3) Tunnel operational philosophy such as bidirectional flow and congestion management
(4) Fire protection systems
(5) Fire properties and characteristics
(6) Environmental conditions

The design fire scenario is not necessarily the worst fire that can occur. Engineering judgment should be used to establish the probability of occurrence and the ability to achieve practical solutions. Therefore, different scenarios are often used for various safety systems.

Δ Table A.11.4.1 Fire Data for Typical Vehicles

Vehicles	Experimental HRR Peak HRR (MW)	Experimental HRR Time to Peak HRR (min)	Representative HRR Peak HRR (MW)	Representative HRR Time to Peak HRR (min)	Experimental HRR with FFFS Peak HRR (MW)	Experimental HRR with FFFS Time to Peak HRR (min)
Passenger car	5–10	0–54[a]	8	10	—	—
Multiple passenger car	10–20	10–55[b]	15	20	10–15[g]	35[g]
Bus	25–34[c]	7–14	30	15	20[g,h]	—
Heavy goods truck	20–200[d]	7–48[e]	150	15	15–90[g]	10–30[g]
Flammable/ combustible liquid tanker	200–300	–	300	–	10–200[f]	

(1) The designer should consider the rate of fire development (peak HRR might be reached within 10 minutes), the number of vehicles that could be involved in the fire, and the potential for the fire to spread from one vehicle to another.
(2) Temperatures directly above the fire can be expected to be as high as 1000°C to 1400°C (1832°F to 2552°F).
(3) The HRR might be greater than in the table if more than one vehicle is involved.
(4) A design fire curve should be developed to satisfy each specific engineering objective in the design process (e.g., fire-life safety, structural protection).
(5) A catastrophic fire event within the tunnel can result in a fire size with a larger HRR than that shown in the table.
(6) If an FFFS is installed in accordance with Chapter 9, the AHJ can reduce the values for HRR for design purposes based on an engineering analysis and full-scale fire tests. Items to consider in doing this are the following:
(a) Activation time (time from start of fire to steady state, full flow discharge of FFFS)
(b) Resilience
(c) Reliability
[a]Experiments show that 60 percent of the tested individual passenger cars reach peak HRR within 20 minutes and 83 percent within 30 minutes.
[b]Experiments show that 70 percent of the tested multiple passenger cars reach peak HRR within 30 minutes.
[c]Very few tests have been done with buses, but real fires indicate that these experimental values can be higher.
[d]The range of peak HRR and the rate of fire growth are affected by the type and amount of cargo and the container type protecting the cargo. All types of covers of the cargo will delay the fire growth rate. The peak HRR is determined by the fire exposed surface area of the cargo. For most solid cargo materials it varies from 0.1 MW/m^2 for wood to 0.5 MW/m^2 for plastics. In experiments involving 14 tests, in 85 percent of the tested cases the peak HRR was equal to or less than 130 MW, and in 70 percent of the tested cases the peak HRR was equal to or less than 70 MW.
[e]Experiments show that 85 percent of the tested truck loads reached peak HRR within 20 minutes.
[f]Scientific test data with large pool fires is limited, but FFFS with foam additives (AFFF) are known to improve the performance of FFFS.
[g]The experimental tests of FFFS show different HRR measurements depending on system type, fire scenario, activation time, fuels, and ventilation strategies. These are typical values measured in various test programs including water mist and water spray deluge systems.
[h]This value is based on convective HRR only. All other values are based on total HRR. Therefore, the total HRR can be anticipated to be higher than this value.
Cheong, M. K., W. O. Cheong, K. W. Leong, A. D. Lemaire, L. M. Noordijk, "Heat Release Rates of Heavy Goods Vehicle Fire in Tunnels," BHR Group, Barcelona, 2013.
Guigas, X., A. Weatherill, C. Bouteloup, and V. Wetzif, "Dynamic fire spreading and water mist tests for the A86 East tunnel – description of the test set up and overview of the water mist tests Taylor & Francis Group, London, 2005.
Ingason, H. and A. Lönnermark, "Heat Release in Tunnel Fires: A Summary," *Handbook of Tunnel Fire Safety*, 2nd edition, 2012.
Ingason, H., Y. Z. Li, and A. Lönnermark, *Tunnel Fire Dynamics*, Springer, 2015
Lakkonen, M., A. Feltmann, and D. Sprakel, "Comparison of Deluge and Water Mist Systems from a Performance and Practical Point of View," Graz, Austria, 2014.
SOLIT^2- Safety of Life in Tunnels Research project, SOLIT Research Consortium, Germany, 2012.

A.11.4.2 The design fire scenario size selected has an effect on the magnitude of the critical air velocity necessary to prevent backlayering. A method for calculating the critical velocity is described in Annex D.

A.11.4.3 Emergency ventilation should be sized to meet minimum ventilation requirements with one critical fan out of service, or provide operational measures for smoke management so that life safety is not compromised with one critical fan out of service.

A.11.5.1 Various means can be utilized to ensure that temperatures do not exceed the operational temperature limits of fans and other devices to be used in fire emergencies, including physical separation or the use of water-based fire-fighting systems to limit fire gas temperatures.

A.11.5.3 Because the fan or group of fans closest to the fire site is likely to be rendered inoperable by the fire, additional fans should be included in the ventilation design.

A.12.1.1 The power distribution system should be maintained through an approved annual maintenance program. The electrical distribution maintenance program should be consistent with NFPA 70B.

A.12.1.2(1) When selecting a fire-resistive cable, it is important to understand how it will be installed and if it was tested as a complete system, including splices. Cables that are exposed (not embedded in concrete) should be protected using either a metallic raceway or an armor/sheath (see 12.3.1).There are two basic configurations of fire-resistive cables. Cables enclosed by a metallic sheath or armor, such as Type MI or Type MC, are installed without raceways. Cables that are installed in a raceway, such as Type RHW-2, Type TC, or Type CM are tested as a complete system. Regardless of the fire test standard used to evaluate fire-resistive cables that will be installed in a raceway, it is important to consider that the cables are only one part of the system. Other components of the system include, but are not limited to, the type of raceway, the size of raceway, raceway support, raceway couplings, boxes, conduit bodies, splices where used, vertical supports, grounds, and pulling lubricants. Each cable type should be tested to demonstrate compatibility.

Only those specific types of raceways tested should be acceptable for installation. Each cable type that is intended to be installed in a raceway should be tested in both a horizontal and vertical configuration while demonstrating circuit integrity.

A.12.1.2(2) Fire-barrier systems use materials that limit the temperature the circuit will be exposed to, thereby maintaining circuit integrity. These systems can include concrete encased conduits or conduits protected by a passive fire protective material.

A.12.1.5 Guidance for seismic protection can be found in the following documents:

(1) AISC 325, *LRFD Manual of Steel Construction*
(2) ASTM E580, *Standard Practice for Installation of Ceiling Suspension Systems for Acoustical Tile and Lay-in Panels in Areas Subject to Earthquake Ground Motions*
(3) IEEE 693-2005, *Recommended Practices for Seismic Design of Substations*
(4) USACE TI 809, *Seismic Design for Buildings*
(5) ANSI/UL 1598, *Luminaires*
(6) ASCE/SEI 7, *Minimum Design Loads for Buildings and Other Structures*
(7) EN 61508-1, *Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems*

A.12.3.3 Consideration must be given to the wiring methods and other materials installed in supply air ducts to ensure that the supply air is not contaminated with smoke. The cables must still meet the requirements of Section 11.2, but because they can be exposed to constant air flow they must also be tested to NFPA 262 or an equivalent internationally recognized standard when not installed in conduits or armor. Cables that meet the requirements of NFPA 262 can be supported by a covered cable tray without additional protection as long as the cables are listed for cable tray use. Emergency circuits installed in supply air ducts must meet the requirements of 11.1.4.

A.12.3.4 Consideration must be given to all conduits, equipment, and supports installed in exhaust air ducts because of elevated air temperatures. It is not implied that the circuit remains functional when exposed to the elevated temperatures but rather the elements (conduit, equipment, support) inside the exhaust air duct not lose structural integrity, thereby interrupting the ventilation system. For normal circuit wiring, the cables and conductors must comply with Section 11.2. It should be understood that wiring meeting the requirements of Section 11.2 could fail due to the elevated temperature. Emergency circuits installed in exhaust air ducts must meet the requirements of 11.1.4.

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A.12.5 The reliability of the system should be verified by a short-circuit and coordination study, for normal circuits and alternative circuits. The initial study should be verified every 5 years.

A.12.6.1 The emergency lighting system should be maintained in accordance with IES DG4, *Design Guide for Roadway Lighting Maintenance*; NECA/IESNA 502, *Standard for Installing Industrial Lighting Systems*; and NFPA 70B.

A.12.6.5 Lighting can be maintained without interruption by duplicate independent power systems, uninterruptible power supplies, and standby generators.

A.12.6.8 Symbols specified in NFPA 170, Table 4.2, should be included in the egress signage to inform the non-English-speaking portion of the population using the tunnel.

A.12.7 The security of the electrical supply substation to the facility should be in accordance with the recommendations in IEEE 1402, *IEEE Guide for Electrical Substation Physical and Electrical Security*.

The following documents should be consulted for developing the security plan:

(1) NFPA 730, *Guide for Premises Security*
(2) NFPA 731, *Standard for the Installation of Electronic Premises Security Systems*
(3) *NFPA 1600, Standard on Disaster/Emergency Management and Business Continuity/Continuity of Operations Programs*

A.13.2 The complexity of the interface between the operating authorities and the emergency responders should not be underestimated. The knowledge of safety related to a specific tunnel and the responses in case of an accident will differ, depending on the tunnel operator, the emergency services, and the users. Emergency response plans aim to ensure that tunnel users and fire and rescue services are exposed to the least risk.

The tunnel operator understands the features available and should take appropriate action to implement procedures that will minimize the danger to occupants. The operator will call in the emergency services and generally follow a prescribed plan. The development of this plan and how it should be refined through exercises and training should also be addressed. The emergency services need knowledge of the tunnel details, technical systems, and operational possibilities to take control of the situation and begin the rescue operation with maximum safety, with a need to interpret possibly incomplete information in situations that can change rapidly, and to deal with human behavioral problems. More detail can be found in Fire in Tunnels Thematic Network, Technical Report 3: "Fire Response Management," 2004.

A.13.3 See the sample emergency response plan outline provided in Annex F. Although facilities covered by this standard are not considered places of public assembly, the emergency response plan should recognize the need to evacuate individuals, regardless of their physical condition.

For additional information on traffic incident management, visit the Federal Highway Administration website: http://ops.fhwa.dot.gov/eto_tim_pse/about/tim.htm.

N **A.13.3(12)** Concurrent incidents can range from two small vehicles with fires, to several large complex incidents with multiple vehicle fires. Managing concurrent incidents could be affected by the structure, systems, staffing, responders, and emergency operations procedures. For example, a fixed water-based fire-fighting system (FFFS) that has been designed to supply two or more deluge zones for a single fire could allow each zone to be manually operated to manage two separate smaller incidents in different areas of a tunnel. Plans that consider the use of existing resources to manage concurrent incidents might allow the operators to implement a more effective response to concurrent incident situations.

N **A.13.3(18)** Facilities regulated by this standard might be able to continue to operate with a degraded mode of operation. The capabilities of the system when operating in a degraded mode should be assessed. For example, a tunnel ventilation system designed to manage smoke from a heavy goods vehicle with no dangerous goods might be able to manage smoke from cars and small trucks, even when more fans are out of service than what the design requires.

A.13.4 The participating agencies and organizations can vary depending on the governmental structure and laws of the community.

A.13.5 Federal NIOSH 2003–136, "Guidance for Filtration and Air-Cleaning Systems to Protect Building Environments from Airborne Chemical, Biological, or Radiological Attacks," recommends engineering steps to be implemented in design and operational procedures for "extraordinary incidences," which include building protection from airborne chemical, biological, and radiation attacks.

Δ **A.13.5.2** Expanding the OCC functions for it to be a supervising station will allow faster and more coordinated control and monitoring of the various fire-life safety systems. This will expedite emergency functioning by eliminating potential delays from a central supervising station company.

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A.13.7 In addition to using NFPA 1561, consideration should be given to use *NFPA 1600* for planning for incidents.

A.13.8 Exercises are distinct from training events and can include workshops, facilitated policy discussions, seminars, tabletop exercises (TTX), games, modeling and simulations (M&S), drills, functional exercises (Fes), and full-scale exercises.

A.13.8.3 Such programs should involve a competent supervisory staff that is experienced in fire fighting, life safety techniques, and hazardous materials emergencies. Operator workstation simulation software can be developed for training to model all elements of the emergency response plan and size/life safety tunnel features.

U.S. Government publications, FEMA 141, "Emergency Management Guide for Business and Industry," "Homeland Security Exercise and Evaluation Program (HSEEP)," and "National Exercise Program," provide additional information on training and exercises and can be required for some facilities in the United States.

A.14.1.1 When developing rules and regulations, fire, accident, and research experience of the vehicles and cargo of the type expected within the tunnel and particularly of goods and vehicles not normally characterized as hazardous or otherwise regulated should be considered. Some types of cargoes not normally considered hazardous can, under certain circumstances in confined spaces within tunnels, behave like or be the equivalent of hazardous materials in terms of rate of fire growth, intensity of the fire, discharge of noxious materials, destruction of infrastructure, and a threat to users' safety.

A.14.1.3 The following provides further details on the listed items in 14.1.3:

(1) *Population density.* The population potentially exposed to a hazardous material release should be estimated from the density of the residents, employees, motorists, and other persons in the area, using census tract maps or other reasonable means for determining the population within a potential impact zone along a designated highway route. The impact zone is the potential range of effects in the event of a release. Special populations such as schools, hospitals, prisons, and senior citizen homes should, among other things, be considered in the determination of the potential risk to the populations along a highway routing. Consideration also should be given to the amount of time during which an area experiences a heavier population density.
(2) *Type of highway.* The characteristics of alternative hazardous material highway routing designations should be compared. Vehicle weight and size limits, underpass and bridge clearances, roadway geometrics, number of lanes, degree of access control, and median and shoulder structures are examples of characteristics that should be considered.
(3) *Types and quantities of hazardous materials.* An examination should be made of the type and quantity of hazardous materials normally transported along highway routes that are included in a proposed hazardous material routing designation. Consideration should be given to the relative impact zone and the risks of the types and quantities of hazardous materials.
(4) *Emergency response capabilities.* In consultation with the proper fire, law enforcement, and highway safety agencies, consideration should be given to the emergency response capabilities that might be needed as a result of a hazardous material routing designation. The analysis of the emergency response capabilities should be based on the proximity of the emergency response facilities and their capabilities to contain and suppress hazardous material releases within the impact zones.
(5) *Results of consultation with affected persons.* Consideration should be given to the comments and concerns of affected persons and entities during public hearings and consultations conducted in accordance with 14.1.3.
(6) *Exposure and other risk factors.* The exposure and risk factors associated with any hazardous material routing designations should be defined. The distance to sensitive areas should be considered. Sensitive areas include, but are not limited to, homes and commercial buildings; special populations in hospitals, schools, handicapped facilities, prisons, and stadiums; water sources such as streams and lakes; and natural areas such as parks, wetlands, and wildlife reserves.
(7) *Terrain considerations.* Topography along and adjacent to the proposed hazardous material routing designation that might affect the potential severity of an accident, the dispersion of the hazardous material upon release, and the control and cleanup of released hazardous material should be considered.
(8) *Continuity of routes.* Adjacent jurisdictions should be consulted to ensure routing continuity for hazardous material across common borders. Deviations from the most direct route should be minimized.
(9) *Alternative routes.* Consideration should be given to the alternative routes to, or resulting from, any hazardous material route designation. Alternative routes should be examined, reviewed, or evaluated to the extent necessary to demonstrate that the most probable alternative rout-

ing resulting from a routing designation is safer than the current routing.

(10) *Effects on commerce.* Any hazardous material routing designation made in accordance with this section should not create an unreasonable burden on interstate or intrastate commerce.

A.15.1 Periodic testing and mandatory testing after a major fire incident within the facility should be performed in accordance with NFPA 3.

Annex B Tenable Environment

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

B.1 General. The purpose of this annex is to provide guidelines for the evaluation of tenability within the tunnel evacuation paths. Current technology is capable of analyzing and evaluating all unique conditions of each path to provide proper ventilation for pre-identified emergency conditions. The same ventilating devices might or might 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.

B.2 Environmental Conditions. Some factors that should be considered in maintaining a tenable environment for periods of short duration are discussed in B.2.1 through B.2.6.

B.2.1 Heat Effects. Exposure to heat can lead to life threat in three basic ways:

(1) Hyperthermia
(2) Body surface burns
(3) Respiratory tract burns

For use in the modeling of life threat due to heat exposure in fires, it is necessary to consider only two criteria — 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 inhalation of air containing less than 10 percent by volume of water vapor do not occur in the absence of burns to the skin or the face; thus, 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 above 60°C (140°F) that is saturated with water vapor.

The tenability limit for exposure of skin to radiant heat is approximately 2.5 kW/m^2. Below this incident heat flux level, exposure can be tolerated for 30 minutes or longer without significantly affecting the time available for escape. Above this threshold value, the time to burning of skin due to radiant heat decreases rapidly according to equation B.2.1a.

[B.2.1a]

$$t_{Irad} = 4q^{-1.36}$$

where:

t_{Irad} = time to burning of skin due to radiant heat (minutes)
q = radiant heat flux (kW/m^2)

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

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 equation B.2.1a is ±25 percent. Moreover, an irradiance of 2.5 kW/m^2 would correspond to a source surface temperature of approximately 200°C (392°F), which is most likely to be exceeded near the fire, where conditions are changing rapidly.

Calculation of the time to incapacitation under condition of exposure to convected heat from air containing less than 10 percent by volume of water vapor can be made using either equation B.2.1b or equation B.2.1c.

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 convected heat accumulated per minute is the reciprocal of t_{Iconv}.

Convected 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, equation B.2.1b is suggested:

[B.2.1b]

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

where:

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

For unclothed or lightly clothed subjects, it might be more appropriate to use equation B.2.1c:

[B.2.1c]

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

where:

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

Equations B.2.1b and B.2.1c are empirical fits to human data. It is estimated that the uncertainty is ±25 percent.

Thermal tolerance data for unprotected human skin suggest a limit of about 120°C (248°F) for convected heat, above which there is, within minutes, onset of considerable pain along with the production of burns. Depending on the length of exposure, convective heat below this temperature can also cause hyperthermia.

The body of an exposed occupant can be regarded as acquiring a "dose" of heat over a period of time. A short exposure to a high radiant heat flux or temperature generally 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 equation B.2.1d:

[B.2.1d]

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

where:
FED = fraction equivalent dose
t_{Irad} = time (min)
t_{Iconv} = time (min)
$\Delta t_{t_1}^{t_2}$ = change in time (min)

Note 1: In areas within an occupancy where the radiant flux to the skin is under 2.5 kW/m^2, the first term in equation B.2.1d is to be set at zero.

Note 2: The uncertainty associated with the use of equation B.2.1d would depend on the uncertainties associated with the use of the three earlier 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 percent to allow for uncertainties in equations B.2.1b and B.2.1c.
(4) The exposure temperature is constant.
(5) The FED is not to exceed 0.3.

Equations B.2.1c and B.2.1d can be manipulated to provide the following equation:

[B.2.1e]

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

where:
t_{exp} = time of exposure to reach a FED of 0.3 (minutes)
T = temperature (°C)

This gives the results in Table B.2.1.

B.2.2 Air Carbon Monoxide Content. Air carbon monoxide (CO) content is as follows:

(1) Maximum of 2000 ppm for a few seconds
(2) Averaging 1150 ppm or less for the first 6 minutes of the exposure
(3) Averaging 450 ppm or less for the first 15 minutes of the exposure
(4) Averaging 225 ppm or less for the first 30 minutes of the exposure
(5) Averaging 50 ppm or less for the remainder of the exposure

Table B.2.1 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

These values should be adjusted for altitudes above 984 m (3000 ft).

B.2.3 Toxicity. The toxicity of fire smoke should be determined by considering contributing gases, which can act cumulatively.

Δ **B.2.4 Smoke Obscuration Levels.** Smoke obscuration levels should be continuously maintained below the point at which a sign internally illuminated with a luminance of 8.6 cd/m^2 (2.5 fl) is discernible at 30 m (100 ft) and doors and walls are discernible at 10 m (33 ft).

B.2.5 Air Velocities. Air velocities in the enclosed tunnel should be greater than or equal to 0.76 m/sec (150 fpm) and less than or equal to 11.0 m/sec (2200 fpm).

Δ **B.2.6 Noise Levels.** Speech intelligibility during an emergency should be considered in the development of the facility's design and emergency response plan. During an emergency, in addition to emergency responder activities, noise levels resulting from operation of emergency systems such as fixed firefighting and ventilation systems will affect the ability to communicate.

The concern is that at least a minimum level of speech intelligibility be maintained along the emergency evacuation paths to allow for effective communication among first responders and between first responders and stranded or evacuating motorists.

Criteria for noise levels should be established for the various situations and potential exposures particular to the environments addressed by this standard. Speech intelligibility becomes difficult in background sound pressure levels of 85 dBA or greater.

The emergency conditions and response might create regions where voice intelligibility would be difficult or impossible to achieve. Addressing this might include additional noise control measures and acoustical treatment. Alternatively, exceptions for reasons of cost and feasibility could be required for defined limited distances along the evacuation path that are near active noise sources and if necessary, other means of reliable communication might be applied such as strobes or wayfinding signaling to support emergency communication and egress.

In cases where the emergency response plan relies upon voice communication, starting points for various design scenarios as integrated with the emergency response plan could be considered as follows:

(1) Where reliance upon unamplified speech is part of the emergency response plan within a tunnel, the sound pressure level during emergency response from all active systems measured along the path of evacuation at any point 5 ft (1.52 m) above the walking surface should not exceed 85 dBA starting at a project-determined distance from the noise sources. An upper limit of 90 dBA at any point 5 ft (1.52 m) above the evacuation path walking surface could be considered where needed to accommodate challenging locations near noise sources.
(2) Where reliance upon amplified speech is used as part of the emergency response within a tunnel, the sound pressure level of fixed voice communication systems during operation of all active systems measured inside a tunnel along the path of evacuation at any point 5 ft (1.52 m) above the walking surface should achieve a measured speech transmission index (STI) of not less than 0.45 [0.65 common intelligibility scale (CIS)] and an average STI of not less than 0.5 (0.7 CIS) as per D.2.4.1 in *NFPA 72*. Refer to Annex D of *NFPA 72* for further information on speech intelligibility for voice communication systems.

B.3 Geometric Considerations. Some factors that should be considered in establishing a tenable environment in evacuation paths are as follows.

(1) 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 percent. Therefore, in modeling methods a height of at least 2.5 m (8.2 ft) should be maintained above any point along the surface of the evacuation pathway.
(2) The application of tenability criteria at the perimeter of a fire is impractical. The zone of tenability should be defined to apply outside a boundary away from the perimeter of the fire. This distance will depend on the fire heat release rate and could be as much as 30 m (100 ft).

B.4 Time Considerations. The project should develop a time-of-tenability criterion for evacuation paths with the approval of the authority having jurisdiction (AHJ). Some factors that should be considered in establishing this criterion are as follows:

(1) The time for fire to ignite and become established
(2) The time for fire to be noticed and reported
(3) The time for the entity receiving the fire report to confirm existence of fire and initiate response
(4) The time for all people who can self-rescue to evacuate to a point of safety
(5) The time for emergency personnel to arrive at the incident location in the facility
(6) The time for emergency personnel to search for, locate, and evacuate all those who cannot self-rescue
(7) The time for fire fighters to begin to suppress the fire

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

B.5 Egress Calculations. Egress calculations should consider the changes in walking speed produced by smoke.

Annex C Temperature and Velocity Criteria

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

C.1 General.

C.1.1 This annex provides criteria for the protection of motorists, employees, and fire fighters with regard to air temperature and velocity during emergency situations.

C.1.2 The quantitative aspects of the criteria for emergency situations are largely arbitrary because there are no universally accepted tolerance limits that directly pertain to air temperature and velocity. Instead, tolerance limits vary with age, health, weight, sex, and acclimatization.

C.2 Air Temperature Criteria.

C.2.1 Motorists should not be exposed to maximum air temperatures that exceed 60°C (140°F) during emergencies. It is anticipated that an air temperature of 60°C (140°F) places a physiological burden on some motorists, but the exposure also is anticipated to be brief and to produce no lasting harmful effects.

C.2.2 Studies of the severity of tunnel fires with respect to human environmental criteria demonstrate that air temperature in the absence of toxic smoke is a limiting criterion for human survival.

C.3 Air Velocity Criteria.

C.3.1 The purpose of ventilation equipment in a tunnel emergency is to sweep out heated air and to remove the smoke caused by fire. In essentially all emergency cases, protection of the motorists and employees is enhanced by prompt activation of emergency ventilation procedures as planned.

C.3.2 When ventilation air is needed in evacuation routes, it might be necessary to expose motorists to air velocities that are high. The only upper limit on the ventilation rate occurs when the air velocity is great enough to create a hazard to persons walking in such an airstream. According to the descriptions of the effects of various air velocities in the Beaufort scale, motorists under emergency conditions can tolerate velocities as great as 11 m/sec (2200 fpm).

C.3.3 The minimum air velocity within a tunnel section that is experiencing a fire emergency should be sufficient to prevent backlayering of smoke (i.e., the flow of smoke in the upper cross-section of the tunnel in the opposite direction of the forced ventilation air).

C.3.4 Increasing the airflow rate in the tunnel decreases the airborne concentration of potentially harmful chemical compounds (referred to by the general term *smoke*). The decrease in concentration is beneficial to people exposed to smoke. However, a situation can arise in which the source is completely removed and smoke poses no threat of exposure to motorists; actuating any fans can draw the existing smoke to the evacuation routes. Under these conditions, fans should not be activated until it is safe to do so. A rapid and thorough communications system is needed so that the responsible personnel can make proper judgments.

C.3.5 The effectiveness of an emergency ventilation system in providing a sufficient quantity of noncontaminated air and in minimizing the hazard of smoke backlayering in an evacuation pathway is a function of the fire load. The fire load in a tunnel results from the burning rate of a vehicle(s), which, in turn, is a function of the combustible load (in British thermal units) of the vehicle.

Annex D Critical Velocity Calculations

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

Δ **D.1 General.** The critical velocity can be calculated according to Equation D.1:

Δ **[D.1]**

$$\frac{u}{\sqrt{gH}}=\begin{cases}0.81\left(\dfrac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}}\right)^{1/3}\left(\dfrac{H}{W}\right)^{1/12} e^{\left(-\frac{L_b}{18.5H}\right)}, & \dfrac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}}\leq 0.15\left(\dfrac{H}{W}\right)^{-1/4}\\ 0.43 e^{\left(-\frac{L_b}{18.5H}\right)}, & \dfrac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}}> 0.15\left(\dfrac{H}{W}\right)^{-1/4}\end{cases}$$

where:

ρ_a = ambient density (kg/m^3)
C_p = heat capacity (kJ/kg K)
g = gravitational acceleration (m/sec^2)
H = tunnel height (m)
L_b = backlayering length (m), where $L_b = 0$ defines critical velocity (no backlayering of smoke), and $L_b \neq 0$ defines confinement velocity (velocity corresponding to the controlled backlayering length)
T_a = ambient gas temperature (K)
u = longitudinal velocity (m/sec)
$\dot{Q}$ = total heat release rate (HRR) (kW)
W = tunnel width (m)

The effect of the tunnel grading is obtained by multiplying the calculated critical velocity, u_c, by the grade factor, K_g, given in Figure D.1.

Example:

Assume a road tunnel that is 5 m in height (H) with a width (W) of 12 m. Calculate the critical velocity (L_b = 0 m) for a 30 MW heat release rate, as well as the velocity required to obtain L_b = 30 m [*see B.3(2)*]. Ambient values include: ρ_a = 1.2 kg/m^3; C_p = 1 kJ/kg K; g = 9.81 m/sec^2; T_a = 293 K; and roadway grade is 4 percent.

Solution:

First, establish which critical velocity relationship to apply by solving:

N

$$\frac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}}\leq 0.15\left(\frac{H}{W}\right)^{-1/4} \text{ or } \frac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}}> 0.15\left(\frac{H}{W}\right)^{-1/4}$$

Since $\dfrac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}} = 0.487$ is greater than $0.15\left(\dfrac{H}{W}\right)^{-1/4} = 0.187$, the lower equation in Equation D.1 should be used.

Therefore, u is solved in $\dfrac{u}{\sqrt{gH}} = 0.43e^{\left(-\frac{L_b}{18.5H}\right)}$ with the result that u = 3.01 m/sec (592.5 fpm) where L_b = 0 m. For L_b = 30 m, the corresponding velocity is u = 2.18 m/sec (429.1 fpm).

The grade factor (K_g) according to Figure D.1 is 1.1, which means that the calculated critical velocity is 3.3 m/sec (649.6 fpm) and the corresponding velocity is 2.4 m/sec (472.4 fpm).

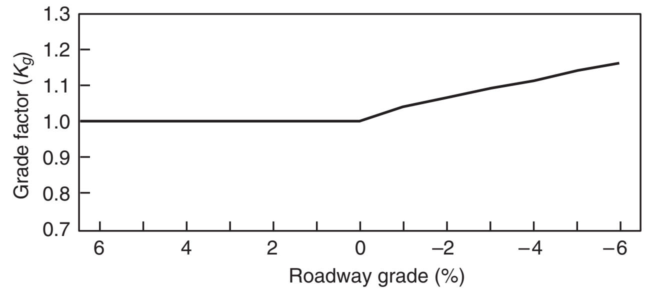

FIGURE D.1 Grade Factor for Determining Critical Velocity.

See further information in the following:

(1) Li Y. Z., Ingason H., "Effect of cross section on critical velocity in longitudinally ventilated tunnel fire," *Fire Safety Journal*, 2017, 91: 303-311.
(2) Li Y. Z., Lei B., Ingason H., "Study of critical velocity and backlayering length in longitudinally ventilated tunnel fires," *Fire Safety Journal*, 2010, 45: 361-370.

Annex E Fixed Water-Based Systems in Road Tunnels

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

E.1 General. This annex provides considerations for the incorporation of fixed water-based fire-fighting systems in road tunnels.

E.2 Fixed Water-Based Systems. Equipment permanently attached to a road tunnel that, when operated, has the intended effect of reducing the heat release and fire growth rates, is able to spread an extinguishing agent in all or part of the tunnel using a network of pipes and nozzles.

Fixed water-based fire-fighting systems should be used as a component of an integrated fire engineering approach to fire protection to reduce the rate of fire growth and the ultimate heat release rate.

Examples of fixed water-based fire-fighting systems include deluge systems, mist systems, and foam systems.

Δ **E.3 Background.** Fixed water-based fire-fighting systems (FFFS) in tunnels have had a renaissance in the past 10 to 15 years. Prior to that time, there were few of these systems installed in tunnels except in Japan and Australia, in addition to a few individual cases. Since then, the efficacy of these systems has been demonstrated through multiple full-scale fire tests, and there has been a substantial amount of material published on the subject. This annex provides some background and considerations on the use of these systems and includes an overview of global practice.

FFFS often consist of open head nozzles on a network of dry pipe that are connected to a water main. Upon detection of the fire, a valve is opened between the water main and the dry pipe to charge the system and release water over the fire incident. FFFS in road tunnels typically come in two water-based variants — deluge and mist — although there are variants on these two main categories. Aqueous film forming foam (AFFF) and other additives are not addressed in this section.

The World Road Association (PIARC) addressed the subject of FFFS in road tunnels in the reports presented at the World Road Congresses held in Sydney (1983), Brussels (1987), and Montreal (1995). In addition, the subject of FFFS was addressed in PIARC's technical reports titled *Fire and Smoke Control in Road Tunnels* (1999), *Systems and Equipment for Fire and Smoke Control in Road Tunnels* (2007), *Road Tunnels: An Assessment of Fixed Fire Fighting Systems* (2008), and *Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations* (2016). FFFS have become recognized as standard technology.

The use of FFFS have increased as reported by PIARC (2016). The following countries now have FFFS installed in road tunnels: Austria, France, the Netherlands, the UK, and Italy (high-pressure water mist); Denmark (low-pressure water mist), Spain and Finland (deluge and high-pressure water mist); and Sweden (deluge). The design of FFFS is based on full-scale fire tests in European tunnels. Some countries have developed their own standards for FFFS in road tunnels that define minimum requirements, for example, Austria's RVS 09.02.51, *Ortsfeste Brandbekämpfungsanlagen*, July 2014).

In Australia, low-pressure, deluge-type FFFS are installed in all major urban road tunnels. The Australian view is that it is more likely that small fires, if not suppressed, could develop into large, uncontrollable fires, particularly since this type of fire development is more typical than large fires that occur instantaneously.

In the Middle East and Asia, several tunnels are protected with FFFS in countries such as the United Arab Emirates, Singapore, Korea, and China, using both high-pressure water mist and low-pressure deluge systems. FFFS also have been installed in road tunnels for more than four decades in Japan, where the decision for a specific tunnel project has to be based on the Japanese safety standards. In Japan, FFFS are required in all tunnels longer than 10,000 m (32,808 ft), and in shorter tunnels longer than 3000 m (9843 ft) with heavy traffic.

FFFS are also currently installed in Africa, including the tunnels under the Suez Canal in Egypt.

Many tunnels are protected with FFFS in North America. Low-pressure deluge systems are typically used and have been installed in many new tunnels since 2008. In addition, there are a few existing tunnels that have been rehabilitated. There are also a few older deluge systems that have been decommissioned due to age and maintenance of aging systems.

E.3.1 In the past, the use and effectiveness of fixed water-based fire-fighting systems in road tunnels were not universally accepted. It is now acknowledged that fixed water-based fire-fighting systems are highly regarded by fire protection professionals and fire fighters and can be effective in controlling a fuel road tunnel fire by actually limiting the spread of the fire. One of the reasons why most countries were reluctant to use fixed water-based fire-fighting systems in road tunnels is that most fires start in the motor compartment of a vehicle, and fixed water-based fire-fighting systems are of limited use in suppressing the fire until the fire is out in the open. Fixed water-based fire-fighting systems can be used, however, to cool down vehicles, to stop the fire from spreading to other vehicles (i.e., to diminish the fire area and property damage), and to stop secondary fires in tunnel lining materials. Experiences from Japan show that fixed water-based fire-fighting systems have been extremely effective in cooling down the area around the fire, so that fire fighting can be performed more effectively.

E.3.2 There is general agreement that, in many cases, the inclusion of water-based fire-fighting systems can act as a valuable component of the overall fire-life safety system in a tunnel. Some of the benefits and capabilities of water-based fire-fighting systems include the following:

(1) *Minimizing fire spread.* Water-based fire-fighting suppression or control systems 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) *Fire suppression and cooling.* If designed accordingly, a water-based fire-fighting suppression system suppresses the fire and cools the tunnel environment to provide more time for evacuation and enable fire fighters to access the fire. Early operation of a water-based fire-fighting system is important in achieving this objective. For example, a heavy goods vehicle fire needs only 10 minutes to exceed 100 MW and 1200°C (2192°F), which are fatal conditions.
(3) *Improved conditions for first responders.* The cooling and radiation-shielding effects of water sprays aid in manual fire-fighting and rescue operations by reducing the thermal exposure.
(4) *Improved performance of ventilation systems.* The cooling of hot products of combustion provided by properly designed water-based fire suppression systems may increase the actual capacity of ventilation systems due to the higher density of cooled products of combustion.
(5) *Reduced fire exposure to structure.* When a fixed fire-fighting system is operated, it is possible to interrupt the fire growth rate, as a result reducing the peak temperatures and their duration occurring at the surface of any exposed structure.

E.3.3 The impact of water-based fire-fighting systems may have additional consequences beyond those listed in E.3.2 that should be considered. For example:

(1) *Reduced stratification.* The cooling and loss of buoyancy resulting from the discharge of water-based fire-fighting systems may lead to destratification of the smoke layer, where such stratification occurs. Normal air movement in the tunnel accelerates this process. However, by limiting the spread of fires, water-based fire-fighting systems reduce the total quantity and rate of smoke generated.
(2) *Testing and maintenance requirements.* Water-based fire-fighting systems will require some maintenance. Proper system design can minimize these requirements. 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.

E.4 Recommendations.

E.4.1 Application. Fixed water-based fire-fighting systems should be considered as part of a package of fire-life safety measures in long or busy tunnels where an engineering analysis demonstrates that an acceptable level of safety can be achieved. The tunnel operator and the local fire department or authority having jurisdiction (AHJ) should consider the advantages and disadvantages of such systems as they apply to a particular tunnel installation.

E.4.2 System Operation. To help ensure against accidental discharge, the fixed water-based fire-fighting system can be designed as a manually activated deluge system with an automatic release after a time delay. To prevent development of a major fire, the time delay should not exceed 3 minutes. The piping should be arranged using interval zoning so that the discharge can be focused on the area of incident without necessitating discharge for the entire length of the tunnel. If foam is applied, each zone should be equipped with its own proportioning valve set to control the appropriate water and foam mixture percentage.

Nozzles should provide an open deluge and be spaced so that coverage extends to roadway shoulders and, if applicable, maintenance and patrol walkways. The system should be designed with enough water and/or foam capacity to allow operation of at least two zones in the incident area. Zone length should be based on vehicle length and hydraulic analysis and should be coordinated with detection and ventilation zones. Piping should be designed to allow drainage through nozzles after flow is stopped.

E.4.3 System Control. It can be assumed that a full-time, attended control room is available for any tunnel facility in which safe passage necessitates the need for fixed water-based fire suppression system protection. Therefore, consideration should be given to human interaction in the fixed water-based fire suppression system control and activation design to ensure against false alarm and accidental discharge. Any automatic mode of operation can include a discharge delay to allow incident verification and assessment of in-tunnel conditions by trained operators.

E.4.3.1 An integrated graphic display of the fixed water-based fire-fighting system zones, fire detection system zones, tunnel ventilation system zones and limits, and emergency access and egress locations should be provided at the control room to allow tunnel operators and responding emergency personnel to make appropriate response decisions.

Δ **E.5 Summary of Research Work Research Work.** Fixed water-based fire-fighting systems (FFFS) have been tested in a number of full-scale fire tests. Multiple countries have tested various water application rates for multiple types of fuel loads. Table E.5 provides a summary of research work that has been performed; it should not be considered comprehensive.

The inclusion of an appropriate FFFS deluge nozzle system requires consideration of a range of tunnel-specific factors and their interactions, including the following:

(1) Ventilation regime (e.g., wind speeds and direction)
(2) Tunnel height
(3) Nozzle installation height
(4) Expected fire load
(5) Environmental conditions (e.g., corrosion and freezing)
(6) Water supply
(7) Water application rate
(8) Performance criteria (e.g., structure protection and tenability)

•

E.6 Fire Test Protocols. While there are not currently any standard fire test protocols for the evaluation of fixed water-based fire-fighting systems intended for installation in road tunnels, ongoing work in Europe has resulted in an "ad hoc" series of tests intended to quantify system performance. Guidance for fire test procedures and test arrangements has been published in following reference documents:

Engineering Guidance for a Comprehensive Evaluation of Tunnels with FFFS, Annex 7: "Fire Tests and Fire Scenarios for Evaluation of FFFS" v. 2.1 by SOLIT Research Consortium, Germany, 2012.

"Large Scale Fire Tests with Fixed Fire Fighting System in Runehamar Tunnel," by Ingason H., G. Appel, and Y. Z. Li, SP Technical Research Institute of Sweden, 2014.

E.6.1 Class B Fire Scenario.

E.6.1.1 The purpose of the Class B scenario is to evaluate the ability of the system to provide cooling for cases where significant reduction in fire size is challenging, such as shielded hydrocarbon pool fires.

E.6.1.2 The Class B fire scenario should be based upon a partly shielded pool fire with a nominal steady state output of at least 25 MW.

E.6.2 Class A Fire Scenario. The Class A fire scenario is intended to evaluate the ability of a fixed water-based fire-fighting system to provide fire suppression or fire control. This scenario employs a simulated heavy goods vehicle filled with wooden pallets.

E.6.3 All tests should be supervised by an accredited independent third party. The final test report should be prepared and signed by the third party. The test report should include, at the very least, details of the following:

(1) Name and address of the independent third party that has been considered acceptable by the authorities having jurisdiction
(2) Detailed drawings of the test tunnel
(3) Detailed drawings of the tested water-based fire-fighting system
(4) Layout parameters for the tested water-based fire-fighting system
(5) Type and size of fire loads
(6) Method of ignition of fire loads
(7) Details of the position of the fire loads in the tunnel
(8) Preburn time
(9) Method of activation of the water-based fire-fighting system
(10) Ventilation conditions (type, velocity)
(11) Temperatures continuously before, during, and after testing at distances of 5 m (16.4 ft), 10 m (32.1 ft), 20 m (65.6 ft), and 40 m (131.2 ft) on the downstream side and at distances of 5 m (16.4 ft), 10 m (32.1 ft), 20 m (65.6 ft), and 40 m (131.2 ft) on the upstream side; distances are measured from the end of the fire load; temperatures are measured at two positions in the cross-section of the tunnel at heights of 1 m (3.3 ft), 2 m (6.6 ft), and 3 m (10 ft) above the road surface and 0.15 m below the ceiling
(12) Radiant heat continuously before, during, and after testing at both ends of the activated WFS section
(13) O_2, CO_2, and CO and water vapor concentration continuously before, during, and after testing approximately 40 m (131.2 ft) at the downstream side of the fire over the cross-section
(14) Estimates of fire heat release rate based upon oxygen consumption calorimetry measurements made during the test
(15) Visibility in the tunnel before, during, and after the tests

N Table E.5 Summary of the Major Research Programs with FFFS

Program Name	Year	Location	System Type	Application Rate	Fire Load Class and Potential HRR in Free Burn Without Suppression
Offenegg [1]	1965	Switzerland	Deluge	Not known or confidential	Class B
PWRI Tests [2]	1980	Japan	Deluge	6 mm/min	Vehicles
Memorial Tunnel Fire Ventilation Test Program [3]	1995	Memorial Tunnel, West Virginia, USA	Deluge (AFFF)	2.4–3.8 mm/min	Class B
2nd Benelux Tests [4]	2001	Benelux Tunnel, The Netherlands	Deluge	12.5 mm/min	Vehicles loaded with wood pallets (40 MW)
Shimizu Tests [5]	2001	Japan	Deluge	6 mm/min	Class B and vehicles
A86 Test Program [6]	2003	VSH, Switzerland	High-pressure water mist	0.47 lpm/m^3	Vehicles (5–30 MW)
UPTUN [7]	2004	DMT, Germany	Sprinkler water curtain, high-pressure water mist	NA	Class A and B
UPTUN [8]	2004	IF Tunnel, Norway	Low- and high-pressure water mist	1.1–3.2 mm/min (low-pressure) 0.5–2.3 mm/min (high-pressure)	Class A and B (25 MW)
A86, Paris Test Program [9]	2005	VSH, Switzerland	High-pressure water mist	0.47 lpm/m^3	Vehicles
Scale Tests [10]	2005	SP, Boras, Sweden	Deluge	NA	Class A
A73 Tests (CAF)	2005	Runehamar, Norway	CAF	Not known or confidential	Class A
M30, Madrid Test Program [11]	2006	San Pedro de Anes, Spain	High-pressure water mist	0.5–0.72 lpm/m^3	Class A and B (100 MW)
Intermediate Scale Test Campaign [12]	2006	CSTB, Paris	High-pressure water mist	0.4–0.8 lpm/m^3	Class A and B
SOLIT [13]	2006	San Pedro de Anes, Spain	High-pressure water mist	Not known or confidential	Class A and B (185 MW)
A73 Tests [14]	2008	Runehamar, Norway	High-pressure water mist	Not known or confidential	Class A and B (150 MW)
University of Carleton [15]	2009	National Research Council Canada	Deluge	4–14 mm/min	Propane
Dartford Crossing – UK Highways Agency [16]	2010	San Pedro de Anes, Spain	High-pressure water mist	Not known or confidential	Class A (100 MW)
Eurotunnel Tests [17]	2010	San Pedro de Anes, Spain	High-pressure water mist	Not known or confidential	Class A (>200 MW)
Singapore Test Programs [18]	2012	San Pedro de Anes, Spain	Deluge	8–12 mm/min	Class A (150 MW)
SOLIT^2 [19]	2012	San Pedro de Anes, Spain	High-pressure water mist	Not known or confidential	Class A and B (150 MW)
MontBlanc Tests [20]	2012	San Pedro de Anes, Spain	Low- and high-pressure water mist and deluge	Not known or confidential	Class A and B (60 MW)
IFAB Tests [21]	2012	San Pedro de Anes, Spain	Deluge and high-pressure water mist	12 mm/min (deluge) 3.5 mm/min (high-pressure water mist)	Class A (150 MW)

(continues)

Table E.5 ***Continued***

Program Name	Year	Location	System Type	Application Rate	Fire Load Class and Potential HRR in Free Burn Without Suppression
IFAB Tests – Water spray [22]	2012	San Pedro de Anes, Spain	Low-pressure deluge (AFFF)	10 mm/min	Class B (50 MW)
SP Sweden Deluge [23]	2013	Runehamar, Norway	Deluge	10 mm/min	Class A (80 MW)
SP Sweden Deluge [24]	2016	Runehamar, Norway	Deluge	6–8 mm/min	Class A (80 MW)

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[2] Ingason, H., "Fire testing in road and railway tunnels," in *Flammability Testing of Materials Used in Construction, Transport and Mining*, V. Apte, Editor, Woodhead Publishing, pp. 231-274, 2006.
[3] Bechtel/Parsons Brinckerhoff, *Memorial Tunnel Fire Test Ventilation Program, Comprehensive Test Report*, prepared for Massachusetts Highway Department/Federal Highway Administration, 1995.
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[16] Feltmann, A. and Laibach, D., "Dartford Crossing: High-Pressure Water Mist Technology Sets New Standards in Tunnel Safety," *Tunnel Magazine* 07, pp. 38-46, 2013.
[17] Lakkonen, M., "Fixed fire fighting systems in tunnels — Case study: Channel tunnel (Eurotunnel)," *Proceedings of the World Tunnel Congress 2012* (WTC2012), Bangkok, Thailand, May 20-23, 2012.
[18] Cheong, M., Cheong, W., Leong, K., Lemaire, A., and Tarada, F., *Heat Release Rates of Heavy Goods Vehicle Fires in Tunnels*, 15th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels, Barcelona, Spain, 18-20 September 2013.
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[24] Ingason, H., Li, Y. Z. and Bobert, M., *Large scale fire tests with different types of fixed fire fighting systems in Runehamar tunnel*, SP Report 2016:76.

Annex F Emergency Response Plan Outline

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

F.1 Outline. The following is an outline for a typical emergency response plan:

(1) General
  (a) Purpose
  (b) Background
(2) Emergency response plan
  (a) General
  (b) Elements of the plan
    i. Central supervising station (CSS)
    ii. Alternate CSS
    iii. Incident and activity identification systems
    iv. Emergency command posts
  (c) Operational considerations
  (d) Types of incidents
  (e) Possible locations of incidents
  (f) Incidents on approach roadways
  (g) Incidents within tunnel or facility
(3) Coordination with other responsible agencies
  (a) Fire-fighting operational procedures
  (b) Traffic management
  (c) Medical evacuation plan
  (d) Emergency alert notification plan

Annex G Alternative Fuels

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

G.1 General. Most vehicles currently used in the United States are powered by either spark-ignited engines (gasoline) or compression-ignited engines (diesel). Vehicles that use alternative fuels such as compressed natural gas (CNG), liquefied petroleum gas (LP-Gas), and liquefied natural gas (LNG) are entering the vehicle population, but the percentage of such vehicles is still not large enough to significantly influence the design of road tunnel ventilation with regard to vehicle emissions. However, it is possible that growing concerns regarding the safety of some alternative-fuel vehicles that operate within road tunnels will affect the fire-related life safety design aspects of highway tunnels. See Chapter 11 for requirements for road tunnel ventilation during fire emergencies.

There are a number of standard requirements for these types of systems, and the requirements derive from existing requirements for storage and transport of CNG tanks.

The creation of accepted consensus-based standards for hydrogen tanks is an ongoing process. However, there are current international draft standards available, which provide some insight to what will be required outside the U.S. in the near future.

In the U.S., the primary standards used are FMVSS 304, *Compressed Natural Gas Fuel Container Integrity*, and ANSI NGV2, *American National Standard for Natural Gas Vehicle Containers.* Both of these standards were developed for the approval of compressed natural gas. It is currently being investigated whether FMVSS 304 can be used for hydrogen fuel tanks. In addition, an ANSI HGV standard is under development, which will mirror the NGV standard, but incorporate specific tests for hydrogen gas vehicle containers and system components.

The tests in both of these standards include full-scale fire tests of the containers and their pressure relief devices (PRDs), as well as component reliability testing, such as pressure cycling, impact resistance, drop tests, and hydrostatic burst testing. In addition to the required tests, a quality-control system is required to be administered by an independent third party to ensure that the fuel system components are manufactured in the same manner as when they were approved through testing. Further, the fuel system would be listed and labeled, such that it would be easily recognizable to an authority having jurisdiction (AHJ) as having met these requirements.

In the long run, it should be feasible for regulators to only allow vehicles that carry an approved listing and label to travel through a road tunnel. In the short term, this is unrealistic, since the standards process is under development and there is some level of controversy as to the minimum acceptable design parameters. As a result, in the short term, the decision will be in the hands of the AHJ as to the mitigation measures for dealing with alternative fuels in road tunnels.

Section G.2 provides some highlighted information about selected alternative fuels, Section G.3 provides some additional information about possible mitigation measures, and Section G.4 provides a brief discussion of applicable codes and standards, as well as recent research into the hazards of alternative fuels.

G.2 Alternative Fuels. It is evident that the use of vehicles powered by alternative fuels (i.e., fuels other than gasoline or diesel) will continue to increase. Of the potential alternative fuels, LP-Gas and hybrid electric currently are the most widely used. Under the Energy Policy Act of 1992 and the Clean Air Act Amendment of 1990, the following are considered potential alternative fuels:

(1) Methanol
(2) Hydrogen
(3) Ethanol
(4) Coal-derived liquids
(5) Propane
(6) Biological materials
(7) Natural gas
(8) Reformulated gasoline
(9) Electricity
(10) Clean diesel

The alternative fuels that are considered most viable in the near future are CNG, LP-Gas, LNG, methanol, hydrogen, and electric hybrid.

G.2.1 Compressed Natural Gas. (CNG) CNG has some excellent physical and chemical properties that make it a safer automotive fuel than gasoline or LP-Gas, provided well-designed carrier systems and operational procedures are followed. Although CNG has a relatively high flammability limit, its flammability range is relatively narrow compared to the ranges for other fuels.

In air at ambient conditions, a CNG volume of at least 5 percent is necessary to support continuous flame propagation, compared to approximately 2 percent for LP-Gas and 1 percent for gasoline vapor. Therefore, considerable fuel leakage is necessary in order to render the mixture combustible.

Furthermore, fires involving combustible mixtures of CNG are relatively easy to contain and extinguish.

Since natural gas is lighter than air, it normally dissipates harmlessly into the atmosphere instead of pooling when a leak occurs. However, in a tunnel environment, such dissipation can lead to pockets of gas that collect in the overhead structure. In addition, since natural gas can ignite only in the range of 5 percent to 15 percent volume of natural gas in air, leaks are not likely to ignite due to insufficient oxygen.

Another advantage of CNG is that its fueling system is one of the safest in existence. The rigorous storage requirements and greater strength of CNG cylinders compared to those of gasoline contribute to the superior safety record of CNG automobiles.

An incident with a CNG-propelled bus in the Netherlands [Fire in a CNG bus (Brand in een aardgasbus, 2012)] highlighted the issue and associated risk of possible jet fires as a consequence of the pressure release valve operation.

G.2.2 Liquefied Petroleum Gas (LP-Gas). There is a growing awareness of the economic advantages of using LP-Gas as a vehicular fuel. These advantages include longer engine life, increased travel time between oil and oil filter changes, longer and better performance from spark plugs, nonpolluting exhaust emissions, and, in most cases, mileage that is comparable to that of gasoline. LP-Gas is normally delivered as a liquid and can be stored at 38°C (100.4°F) on vehicles under a design pressure of 1624 kPa to 2154 kPa (250 psi to 312.5 psi). LP-Gas is a natural gas and petroleum derivative. One disadvantage is that it is costly to store because a pressure vessel is needed. Also, where LP-Gas is engulfed in a fire, a rapid increase in pressure can occur, even if the outside temperature is not excessive relative to the gas–vapor pressure characteristics. Rapid pressure increase can be mitigated by venting the excessive buildup through relief valves. In Australia a significant proportion of the vehicle fleet uses LPG-powered vehicles. Alternative-powered vehicles are marked by colored labels on their registration plates. No restrictions on use of such vehicles exist in Australia. In Australia, the only impact on managing these vehicles is by alternative procedures for incident response by emergency services.

G.2.3 Methanol. Currently, methanol is used primarily as a chemical feedstock for the production of chemical intermediates and solvents. Under EPA restrictions, it is being used as a substitute for lead-based octane enhancers in the form of methyl tertiary-butyl ether (MTBE) and as a viable method for vehicle emission control. MTBE is not available as a fuel substitute but is used as a gasoline additive.

The hazards of methanol production, distribution, and use are comparable to those of gasoline. Unlike gasoline, however, methanol vapors in a fuel tank are explosive at normal ambient temperature. Saturated vapors that are located above nondiluted methanol in an enclosed tank are explosive at 10°C to 43°C (50°F to 109.4°F). A methanol flame is invisible, so a colorant or gasoline needs to be added to enable detection.

Δ **G.2.4 Hydrogen.** Hydrogen is one of the most attractive alternative fuels due to its ability to power fuel cells in vehicles, the abundant availability, and the potential higher efficiency in vehicles. Hydrogen can be used to power vehicles in the form of fuel cells or as replacement fuel in internal combustion engines. 2.2 lb (1 kg) of hydrogen gas has about the same energy as 1 gallon of gasoline. The first commercially deployed hydrogen powered vehicles employ fuel cells to convert hydrogen into electricity to power an electric motor. For a driving range of 300 miles (450 km) or more, a light-duty fuel cell vehicle must carry approximately 11 lb(5 kg) of hydrogen. Commercially available storage technologies typically include high-pressure tanks for compressed hydrogen gas up to 70 MPa (10,000 psi)Fuel cell electric vehicles (FCEVs) have evolved from a demonstration to commercial technology. Several OEMs now sell or lease FCEVs, and networks of hydrogen fueling stations have been constructed on both US coasts with plans to provide fueling service to the entire country.

In comparison with gasoline, hydrogen has a much wider flammability range (4 percent to 75 percent by volume) and explosive limit. The minimum ignition energy of hydrogen in air is about an order of magnitude (by a factor of 10) less than that of gasoline vapor. A static electric spark such as by the human body or from a vehicle tailpipe is sufficient to ignite hydrogen. As the density is only about 7 percent of air, hydrogen release in atmosphere usually results in rapid dispersion and mixing to a nonhazardous concentration. However, accumulation of hydrogen in stagnant space that cannot be ventilated is a fire and explosion hazard. A minimum separation distance from the ceiling or explosion proofing should be considered for such electrical equipment.

Emergency response to an incident involving hydrogen fuel leak or fire requires necessary training, such as recognizing the hydrogen tank, high-voltage battery, or capacitor pack that might be present on the incident vehicle. The NFPA website shown below provides specific emergency response information on commercially available FCEVs. The H2 Tools website shown below provides training materials for emergency responders that can be used to prepare for incidents involving FCEVs. See the following sites for information on emergency response and emergency response training for FCEVs:

(1) H2 Tools: https://h2tools.org/content/training-materials
(2) NFPA: http://www.nfpa.org/training-and-events/by-topic/alternative-fuel-vehicle-safety-training
(3) *Hydrogen Fuel Cell Electric Tunnel Safety Study*, C. LaFleur et al., Sandia National Laboratories SAND2017-11157, October, 2017

N **G.2.4.1 Hydrogen Behavior Compared to Other Fuels.** Table G.2.4.1 provides information on hydrogen properties relative to other alternative fuels and gasoline.

Δ **G.2.5 Electric and Electric Hybrid.** Executive Order 13423 signed in 2007 directed federal agencies to use plug-in hybrid electric vehicles (PHEVs) when their cost becomes comparable to non-PHEVs. PHEVs combine the benefits of pure electric and hybrid electric vehicles, which allows on-board energy storage devices be charged either by plugging into the electric grid or through an auxiliary power unit (APU), using replenishable fuels including certain types of alternative fuels such as CNG or hydrogen. Hybrid electric vehicles (HEVs) offer better fuel economy and lower emission than vehicles using fossil fuels, while electricity produces zero tailpipe emission. Efficiency in energy storage, transmission, and conversion is critical regardless of electric vehicle types. Both battery EVs and gasoline-electric HEVs have been commercially available for a number of years. Due to the introduction of electric drive, energy storage, and conversion system in the powertrain, one of the safety considerations is associated with the high-voltage system (e.g., 600 VDC) used for the powertrain, such as electric shock and

N **Table G.2.4.1 Comparative Properties of Hydrogen Fuels**

Properties	Units	Hydrogen[a]	Methane[a]	Propane[a]	Methanol[a]	Ethanol[a]	Gasoline[b]
Chemical formula		H_2	CH_4	C_3H_8	CH_3OH	C_2H_5OH	C_xH_y (x = 4 – 12)
Molecular weight[d,e]		2.02	16.04	44.1	32.04	46.07	100 to 105
Density (NTP)c,d,f	kg/m^3	0.0838	0.668	1.87	791	789	751
	lb/ft^3	0.00523	0.0417	0.116	49.4	49.3	46.9
Viscosity (NTP)[c,d,e]	g/cm-sec	8.81×10^{-5}	1.10×10^{-4}	8.012×10^{-5}	9.18×10^{-3}	0.0119	0.0037 to 0.0044
	lb/ft-sec	5.92×10^{-6}	7.41×10^{-6}	5.384×10^{-6}	6.17×10^{-4}	7.99×10^{-4}	2.486×10^{-4} to 2.957×10^{-4}
Normal boiling point[d,e]	°C	–253	–162	–42.1	64.5	78.5	27 to 225
	°F	–423	–259	–43.8	148	173.3	80 to 437
Vapor specific gravity (NTP)[c,d,g]	air = 1	0.0696	0.555	1.55	N/A	N/A	3.66
Flash point[e,g]	°C	<–253	–188	–104	11	13	–43
	°F	<–423	–306	–155	52	55	–45
Flammability range in air[e,f,g]	vol%	4.0 to 75.0	5.0 to 15.0	2.1 to 10.1	6.7 to 36.0	4.3 to 19	1.4 to 7.6
Autoignition temperature in air[e,g]	°C	585	540	490	385	423	230 to 480
	°F	1085	1003	914	723	793	450 to 900

Notes:
N/A: Not applicable.
[a]Properties of the pure substance.
[b]Properties of a range of commercial grades.
[c]NTP: Normal temperature and pressure [measured at 20°C (68°F) and 1 atmosphere].
[d]Source: NIST Chemistry WebBook, http://webbook.nist.gov/chemistry/
[e]Source: *Alternatives to Traditional Transportation Fuels: An Overview*, DOE/EIA-0585/U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC, June 1994.
[f]Source: *Perry's Chemical Engineers' Handbook*, 7th Edition, McGraw-Hill, 1997.
[g]Source: *Hydrogen Fuel Cell Engines and Related Technologies*, Module 1: Hydrogen Properties, U.S. Department of Energy, 2001. https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm01r0.pdf

short-circuit; the other is the heat generated during battery charging and discharging, which also tends to give off toxic fumes and hydrogen gas; another safety consideration is accidental spill of battery electrolyte.

The main failure mode involving EV and HEV Li-ion battery packs involves thermal runaway events where the batteries self-heat and fail energetically. Thermal runaway results in venting of flammable gases and could result in subsequent fires. Typical cell vent gases consist of a mixture of carbon monoxide, carbon dioxide, hydrogen, methane, hydrogen fluoride, and a number of heavier hydrocarbons including but not limited to ethane, ethylene, and propylene. Recent testing has confirmed that the exact composition of vent gases depends on the battery state-of-charge and battery chemistry [1].

Note also that a number of materials used in the battery, such as lithium, could burn at very high temperature if ignited. These issues have long been recognized and addressed in relevant SAE documents, for example, SAE J2344, *Guidelines for Electric Vehicle Safety*, and UL standards, including battery thermal management and monitoring, proper electrical insulation and structural isolation of the battery compartment, and automatic disconnect for the energy storage system. Similarly, these have also been recognized for maintenance, training, and emergency response. Testing of full-scale mock-up vehicles equipped with EV and HEV battery packs confirmed water to be an effective suppression agent for these types of fires. However, the results confirmed that the amount of water required for suppression was much higher than for standard IC vehicle fires and as high as 2600 gallons [2]. Testing showed that the most effective way to attack EV and HEV fires is to concentrate the water flow onto the battery pack in order to reduce the temperature of the cells and avoid thermal runaway progression and fire re-ignition. When using water to extinguish/suppress an EV battery fire, a large volume of water should be used.

The following documents are referenced in this section:

[1] Colella et., *Electric Vehicle Fires*, International Symposium on Tunnel Safety and Security, 2016.

[2] Fire Protection Research Foundation Report: *Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results.*

Δ **G.3 Additional Considerations.** As the use of alternative fuels in road vehicles increases, each operating agency or AHJ must deal with the issue of whether to permit such vehicles to pass through the tunnel or lower level of a dual-level bridge for which it is responsible. Each alternative fuel type must be considered on its own merit.

Identification of the alternative fuel type used within a vehicle is the first and most critical issue to address. This is a difficult prospect for many agencies. It is not enough to realize that a fire incident involves an alternative fuel vehicle; the fuel must also be identified. Currently there are no national requirements within the United States for a standard placard system identifying the type of fuel. As consequence, if a particular fuel is prevented by regulation from entering a tunnel facility, vehicle identification is important for enforcement of the facility's rules and procedures.

Identification of alternative-fuel vehicles is critical, as the correct emergency response strongly depends upon knowing the hazard posed by a fire incident. Specific emergency response procedures, precautions, and training requirements for each type of alternative-fuel must also be prepared and included as part of the facility emergency response plan.

These should also be coordinated with the local fire department response plan. Examples of alternative fuel vehicle response plans are accessible at http://www.nfpa.org/training-and-events/by-topic/alternative-fuel-vehicle-safety-training. The hazards presented by various alternative fuel fires differ and are fuel dependent. For instance, hydrogen and methanol flames are not easily discernable with the naked eye. High voltage potential in electric vehicles should be recognized. Therefore, emergency response personnel should be provided with training specific to each alternative-fuel vehicle. In addition, the first responder should consider specialty response equipment such as, but not limited to, self-contained breathing apparatus (SCBA), high-voltage gloves, static dissipative equipment, and infrared cameras to visualize a vehicle fire.

Due to the gaseous nature of most alternative fuels, the first responder might be directed to not extinguish the fire, but instead to manage the fire incident. If there is a delayed ignition after gas release, released gases could move away from the vehicle incident. In extreme cases, there might be the formation of flammable gas clouds that could ignite away from the vehicle and, in rare instances, this could lead to a flash fire or more significant overpressure event.

The facility must also review the potential of accumulation of a gaseous fuel. This could be at a low point as in the case of dense gas clouds (e.g. propane, LNG, or CNG) or at a high point as in the case of hydrogen. If alternative fuel vehicles are using the tunnel, these areas should be identified and monitored to prevent unaware personnel from entering an environment with a latent hazard. Tunnel ventilation provides the tunnel facility with one means of mitigation. Tunnel ventilation can provide sufficient air to dilute the escaped fuel to concentrations below the lower flammability limit (LFL). It is necessary to establish a minimum level of ventilation to provide such dilution under all circumstances.

G.4 Informational References. Published research exists to help assess the relative hazard of specific alternative fuels (and fuel systems) and to help develop consensus safety standards for regulators. Subsection O.2.1 references several codes and standards used for alternative fuels as well as a few website resources for new standards in development. Subsection O.2.2 contains a short list of published research in the area of alternative fuels.

This list of references represents a brief summary of some applicable documents, with some emphasis on hydrogen, as that seems to be the fastest growing technology. This list is not meant to be exhaustive. On the other hand, it is meant to be a starting point for document users to understand some of the hazards of alternative fuels, potential mitigation measures, as well as necessary future research.

Annex H The Memorial Tunnel Fire Ventilation Test Program

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

H.1 General. The primary purpose of controlling smoke in a tunnel is to protect life (i.e., to allow safe evacuation of the tunnel). Such protection involves creating a safe evacuation path for motorists and operating personnel who are within the tunnel. The secondary purpose of smoke-control ventilation is to assist fire-fighting personnel in accessing the fire site by providing a clear path to the fire site, if possible.

A tunnel ventilation system is not designed to protect property, although the effect of ventilation in diluting smoke and heated gases, which removes some of the heat, results in reduced damage to facilities and vehicles. The ongoing reduction of vehicle emissions has shifted the focus of the ventilation engineer from a design based on the dilution of emission contaminants to a design based on the control of smoke in a fire emergency.

Despite the increasing focus on life safety and fire control in modern road tunnels, no uniform standards for fire emergency ventilation or other fire control means within road tunnels have been established in the United States.

H.2 Ventilation Concepts. The ventilation concepts that have been applied to highway tunnels have been based on theoretical and empirical values, not on the results of full-scale tests. Therefore, the design approach that is currently used to detect, control, and suppress fire and smoke in road tunnels has become controversial among tunnel design engineers, owners, operators, and fire fighters throughout the world.

While most road tunnels have ventilation systems with smoke-control operating modes, there were limited scientific data to support opinions or code requirements regarding the capabilities of various types of ventilation systems to control heat and smoke effectively.

H.3 Investigations. Engineering investigations of ventilation operating strategies and performance in full-scale fire situations were authorized by the Massachusetts Highway Department (MHD) and the U.S. Federal Highway Administration (USFHA) to be performed in the Memorial Tunnel in West Virginia as a part of the Boston Central Artery/Tunnel Project. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Technical Committee TC 5.9, "Enclosed Vehicular Facilities," identified the need for a comprehensive full-scale test program in the early 1980s.

Technical Committee TC 5.9 was commissioned in 1989 to form a subcommittee, the Technical Evaluation Committee (TEC), to develop a Phase 1 concept report and work scope. The report outlined the objectives of the testing program, which included identification of appropriate means to account for the effects of fire size, tunnel grade and cross-section, direction of traffic flow (unidirectional or bidirectional), altitude, type of ventilation system, and any other parameters that could have a significant influence on determining the ventilation capacity and operational procedures needed for safety in a fire situation.

The establishment of specific approaches to allow for effective reconfiguration of both new and existing tunnel facilities was deemed of equal importance. The goals and test matrices that were developed and documented in the Phase 1 concept report evolved into the test plan described in the following paragraphs.

The purpose of the Memorial Tunnel Fire Ventilation Test Program (MTFVTP) was to develop a database that provides tunnel design engineers and operators with an experimentally proven means to determine the ventilation rates and ventilation system configurations that provide effective smoke control, smoke removal, or both, during a tunnel fire emergency.

A more important purpose of the MTFVTP was to establish specific operational strategies to allow effective reconfiguration of ventilation parameters for existing tunnel facilities. While the life safety issue is paramount, it should be recognized that significant cost differentials exist among the various types of ventilation systems. In the instance where more than one ventilation configuration offers an acceptable level of fire safety, the project's overall life cycle cost needs to be addressed to identify the option with the optimum cost benefit.

In addition, the impact of ventilation systems that cause horizontal roadway airflow on the effectiveness of fire suppression systems (such as foam deluge sprinklers) can be better determined by performing full-scale tests.

H.4 The Test Facility. The Memorial Tunnel is a two-lane, 854 m (2800 ft) highway tunnel located near Charleston, West Virginia, originally built in 1953 as part of the West Virginia Turnpike (I-77). The tunnel has a 3.2 percent uphill grade from the south to the north tunnel portal. The original ventilation system was a transverse type, consisting of a supply fan chamber at the south portal and an exhaust fan chamber at the north portal.

The tunnel has been out of service since it was bypassed by an open-cut section of a new six-lane highway, Interstate 77, in 1987. As part of the MTFVTP, the existing ventilation equipment was removed to allow the installation of new variable-speed, reversible, axial-flow central ventilation fans. The equipment rooms were modified to accept the ventilation components needed to allow supply or exhaust operation from both ends of the tunnel.

There are six fans, three each in the modified north and south portal fan rooms. Each of the fans has a capacity to supply or exhaust 94.4 m^3/sec (200,000 ft^3/min), and the fans are fitted with vertical discharges to direct the smoke away from the test facility and the nearby interstate highway.

The existing overhead air duct, formed by a concrete ceiling above the roadway, is split into longitudinal sections that can serve as either supply or exhaust ducts, and a mid-tunnel duct bulkhead has been installed to allow a two-zone ventilation operation. Openings in the duct dividing wall and duct bulkhead have been designed to create airflow patterns similar to those that would be observed if the dividing wall was not present. The width of the ducts varies linearly along the length of the tunnel to provide maximum area at the point of connection to the fan rooms above the tunnel portals.

High-temperature insulation was applied extensively to various structural elements, including the concrete ceiling and ceiling hangers, all utilities, instrumentation support systems, wiring, gas-sampling lines, closed-circuit television (CCTV) camera cabinets, and all other related items that are exposed to high tunnel fire temperatures.

H.5 Fire Size. Fires with heat release rates ranging from 20 MW (equivalent to a bus or truck fire) to 50 MW [equivalent to a flammable spill of approximately 400 L (100 gal)] to 100 MW [equivalent to a hazardous material fire or flammable spill of approximately 800 L (200 gal)] were produced. The fires were generated in floor-level steel pans.

The actual burning rate differed somewhat from that used for the engineering estimate, due to effects such as heat reradiation from the tunnel walls and varying ventilation flow rates. Therefore, the measured tunnel conditions were interpreted to determine a measured heat release rate. The ventilation systems that were configured and tested under varying flow rates and varying heat release rates, with one or two zones of ventilation, included the following:

(1) Transverse ventilation
(2) Partial transverse ventilation
(3) Transverse ventilation with point extraction
(4) Transverse ventilation with oversized exhaust ports
(5) Natural ventilation
(6) Longitudinal ventilation with jet fans

When the first four series of tests in H.5(1) through H.5(6) were completed, the tunnel ceiling was removed to conduct the natural ventilation tests, which were followed by the installation of jet fans at the crown of the tunnel to conduct the longitudinal jet fan–based ventilation tests.

A fire suppression system intended to be available to suppress the fire in an emergency was installed; however, it was also used during several tests to evaluate the impact of ventilation airflow on the operation of a foam suppression system.

H.6 Data Collection. All measured values were entered into a data acquisition system (DAS) that monitored and recorded data from all field instruments for on-line and historical use.

The measurement of tunnel air temperature was accomplished through the use of thermocouples located at various cross-sections throughout the length of the tunnel.

In total, there were approximately 1450 instrumentation-sensing points. Each sensing point was monitored and recorded once every second during a test, which lasted 20 minutes to 45 minutes.

Approximately 4 million data points were recorded during a single test. All test data was recorded on tapes in a control center trailer, where control operators monitored and controlled each test.

Instrument trees located at ten tunnel cross-sections were designed to measure airflow to a modified ASHRAE traverse method. Additional temperature measurements were taken at five other tunnel cross-sections and at two locations outside of the tunnel portals. The measurement of air velocity in the tunnel under test conditions was accomplished through the use of differential pressure instrumentation. Temperatures in the vicinity of the bidirectional pilot tubes and the ambient pressure were combined with the measured pressure to calculate the air velocity.

A gas-sampling system extracted sample gas from specific tunnel locations to analysis cabinets that were located in the electrical equipment rooms. Sample gases were analyzed within the analysis cabinets for CO, carbon dioxide (CO_2), and total hydrocarbon content (THC). The analyzers were housed in climate-controlled cabinets.

To ensure personnel safety, methane gas could be detected at the test fire location through the use of individual in-situ electromechanical cell–type analyzers at the control trailer. In addition, portable detectors that were capable of detecting CO, total hydrocarbon, oxygen, and methane were provided for the safety of personnel who entered the tunnel after fire tests.

Two meteorological towers that were located outside of the north and south tunnel portals included instrumentation that monitored and recorded ambient dry- and wet-bulb air temperatures, barometric pressure, wind speed, and wind direction.

The weather-related parameters were monitored for over 1½ years to track weather conditions to assist in planning, scheduling, and conducting the tests.

The CCTV system originally included six cameras: two located within the tunnel, two located outside of the tunnel (near the portals), and two located on the north and south meteorological towers. During the tests, another camera was added north of the fire to show smoke movement.

H.7 Conclusions. The MTFVTP represented a unique opportunity to evaluate and develop design methods and operational strategies that lead to safe underground transportation facilities. The comprehensive test program, which began with the initial fire tests in September 1993 and concluded in March 1995, produced data that were acquired in a full-size facility, under controlled conditions, and over a wide range of system parameters.

The findings and conclusions are categorized by ventilation system type and are summarized as follows.

H.7.1 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 up to 100 MW in a 3.2 percent grade tunnel.

The throttling effect of the fire needs to be taken into account in the design of a jet fan longitudinal ventilation system.

Jet fans that were located 51.8 m (170 ft) downstream of the fire were subjected to the following temperatures for the tested fire sizes:

(1) 204°C (400°F) — 20 MW fire
(2) 332°C (630°F) — 50 MW fire
(3) 677°C (1250°F) — 100 MW fire

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

H.7.2 Transverse Tunnel Ventilation Systems. It has been standard practice in the tunnel ventilation industry to design tunnel ventilation systems for fire emergencies that are based on fan capacities expressed in cubic meters per second per lane meter ($m^3/sec \cdot lm$) [cubic feet per minute per lane foot ($ft^3/min \cdot lf$)]. However, the MTFVTP has demonstrated that longitudinal airflow is a major factor in the ability of a ventilation system to manage and control the movement of smoke and heated gases that are generated in a fire emergency.

It was demonstrated in the MTFVTP that dilution as a sole means for temperature and smoke control was not very effective. Some means of extraction should be incorporated. Extraction and longitudinal airflow, where combined, can significantly increase the effectiveness of a road tunnel ventilation system in managing and controlling the movement of smoke.

H.7.3 Single-Zone Transverse Ventilation Systems. Single-zone, balanced, full-transverse ventilation systems that were operated at 0.155 $m^3/sec \cdot lm$ (100 $ft^3/min \cdot lf$) were ineffective in the management of smoke and heated gases for fires of 20 MW 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. The effectiveness of unbalanced, full-transverse ventilation systems is sensitive to the fire location, since there is no control over the airflow direction.

H.7.4 Multiple-Zone Transverse Ventilation Systems. The two-zone transverse ventilation system that was tested in the MTFVTP provided control over the direction and magnitude of the longitudinal airflow. Airflow rates of 0.155 $m^3/sec \cdot lm$ (100 $ft^3/min \cdot lf$) contained high temperatures from a 20 MW fire within 30 m (100 ft) of the fire in the lower elevations of the roadway and smoke within 60 m (200 ft).

H.7.5 Smoke and Heated Gas Movement. 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 — 490 m to 580 m (1600 ft to 1900 ft) during the initial 2 minutes of a fire.

Natural ventilation resulted in the extensive spread of smoke and heated gases upgrade of the fire, but relatively clear conditions existed downgrade of the fire. The spread of smoke and heated gases during a 50 MW fire was considerably greater than for a 20 MW 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, it depends on the tunnel height. In the Memorial Tunnel, smoke traveled between 290 m and 365 m (950 ft and 1200 ft) along the arched tunnel roof before cooling and descending toward the roadway.

The restriction of 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 carbon monoxide was never more critical than smoke or temperature.

The effectiveness of the foam suppression system (AFFF) that was tested was not diminished by high-velocity longitudinal airflow [4 m/sec (800 fpm)]. The time taken for the suppression system to extinguish the fire, with the nozzles located at the ceiling, ranged from 5 seconds to 75 seconds.

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

(1) 107°C (225°F) — 20 MW fire
(2) 124°C (255°F) — 50 MW fire
(3) 163°C (325°F) — 100 MW 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), prefire conditions, and external meteorological conditions.

H.7.6 Enhancements. The ability to extract smoke quickly and from a location that is as close as possible to the fire can significantly reduce the migration of smoke and heat in undesirable directions and can facilitate two-way traffic operations. Localized extraction is possible with the addition of single-point extraction (SPE) openings or oversized exhaust ports (OEP) to transverse ventilation systems.

SPE systems apply to two-way traffic flow with a dependency on the location, size, and spacing of the SPE openings. Smoke and heat that are drawn from the fire to the SPE can pass over or possibly around stalled traffic and vehicle occupants. An SPE that is located upgrade of the fire is very effective in temperature and smoke management. Where the SPE was located downgrade of the fire, only minimal improvement in temperature and smoke conditions over a single-zone, partial transverse exhaust system was achieved.

A single-point opening of 28 m^2 (300 ft^2) was most effective in temperature and smoke management of the tested SPE sizes. Significantly greater smoke and heat spread were observed with a 9.3 m^2 (100 ft^2) opening, compared to the 28 m^2 (300 ft^2) opening.

In the one test in which two single-point openings that were located north of the fire were used, a stagnation zone formed, resulting in smoke accumulation between the extraction openings.

For 20 MW fires, partial transverse exhaust ventilation that was operated with 0.155 m^3/sec · lm (100 ft^3/min · lf), and supplemented with a large [27.9 m^2 (300 ft^2)] single-point opening, limited the smoke and heated gas migration to within 61 m (200 ft) of the fire. A partial transverse exhaust system that was supplemented with oversized exhaust ports and operated with 0.132 m^3/sec · lm (85 ft^3/min · lf) limited high temperatures to within 31 m (100 ft) of the fire and sustained the smoke layer above the occupied zone.

For 50 MW fires, partial transverse exhaust ventilation that was operated with 0.170 m^3/sec · lm (110 ft^3/min · lf), and supplemented with a large [27.9 m^2 (300 ft^2)] single-point opening, limited the smoke and heated gas migration to within 85 m (280 ft) of the fire.

The results of the test program were processed and made available to the professional community for use in the development of emergency tunnel ventilation design and emergency operational procedures in late 1995 in a report titled "Memorial Tunnel Fire Ventilation Test Program: Test Report." In addition, a comprehensive test report was prepared and is available in a CD-ROM format.

Annex I Tunnel Ventilation System Concepts

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

I.1 General. Ventilation is necessary in most road tunnels to limit the concentrations of contaminants to acceptable levels within the tunnel. Ventilation systems are also used to control smoke and heated gases that are generated during a tunnel fire emergency. Some short tunnels are ventilated naturally (without fans); however, such tunnels could necessitate a ventilation system to combat a fire emergency.

I.1.1 This annex provides fire protection engineers with a basic understanding of the various ventilation system concepts usually employed in the ventilation of road tunnels.

I.1.2 The systems used for mechanical or fan-driven ventilation are classified as longitudinal or transverse. A longitudinal ventilation system achieves its objectives through the longitudinal flow of air within the tunnel roadway, while a transverse ventilation system achieves its objectives by means of the continuous uniform distribution or collection, or distribution and collection, of air throughout the length of the tunnel roadway. A transverse ventilation system also experiences some longitudinal airflow; the quantity depends on the type of system. It is recognized that many combinations of longitudinal and transverse ventilation systems exist.

I.2 Longitudinal Ventilation Systems.

I.2.1 A longitudinal ventilation system introduces air into, or removes air from, the tunnel roadway at a limited number of points, such as portal(s), shaft(s), nozzle(s), or other locations, thus creating a longitudinal flow of air along the tunnel roadway. *[See Figure I.2.1(a) through Figure I.2.1(e).]*

I.2.2 Longitudinal ventilation systems can be subclassified as those that use central fans *[see Figure I.2.1(a), Figure I.2.1(d), and Figure I.2.1(e)]* and those that employ local fans or jet fans *[see Figure I.2.1(c)]*.

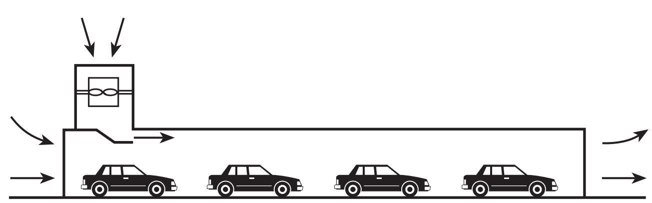

FIGURE I.2.1(a) Longitudinal Ventilation System with Central Fans and Saccardo Nozzle at Entry Portal.

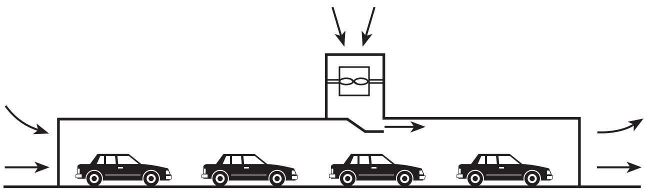

FIGURE I.2.1(b) Longitudinal Ventilation System with Central Fans and Saccardo Nozzle at Midtunnel Location.

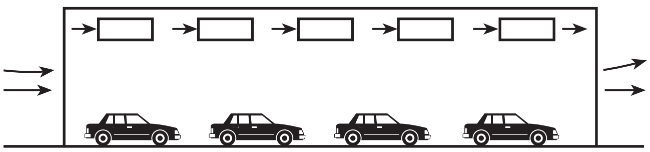

FIGURE I.2.1(c) Longitudinal Ventilation System with Jet Fans.

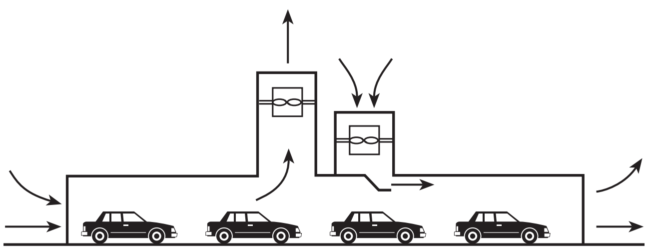

FIGURE I.2.1(d) Longitudinal Ventilation System with Central Fans, Saccardo Nozzle, and Exhaust Shaft.

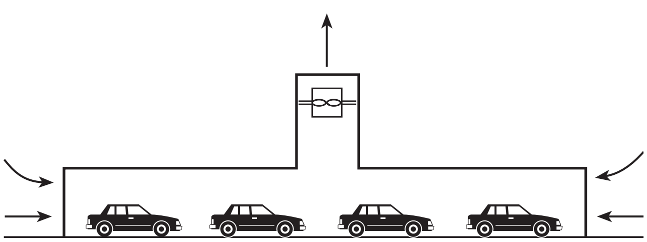

FIGURE I.2.1(e) Longitudinal Ventilation System with Central Fans and Exhaust Shaft.

I.2.2.1 Central-fan longitudinal ventilation systems employ centrally located fans to inject air into the tunnel roadway, through a supply air shaft or a high-velocity nozzle, such as a Saccardo nozzle. The air injection can take place at the entry portal *[see Figure I.2.1(a)]* or at a midtunnel location *[see Figure I.2.1(b)]*. An exhaust air shaft can be combined with the injection nozzle as shown in Figure I.2.1(d).

I.2.2.2 Jet fan–based longitudinal ventilation employs a series of axial flow fans that are typically mounted at the ceiling level of the tunnel roadway *[see Figure I.2.1(c)]*. Such fans, due to the effects of the high-velocity discharge, induce a longitudinal airflow throughout the length of the tunnel roadway.

I.2.3 In all longitudinal ventilation systems, the exhaust gas stream (containing pollutants or smoke) discharges from the exit portal or from the exhaust air shafts.

I.2.4 While evaluating the necessary longitudinal ventilation system thrust in case of fire, it should be assumed that vehicles can be stopped in the tunnel and their presence affects the performance of the ventilation system. The number of stopped vehicles should be assessed according to the predicted traffic mix and the traffic management system available for the tunnel.

I.3 Transverse Ventilation Systems.

I.3.1 Transverse ventilation systems feature the uniform collection and/or distribution of air throughout the length of the tunnel roadway and can be of the full transverse or semitransverse type. In addition, semitransverse systems can be of the supply or exhaust type. *[See Figure I.3.1(a) through Figure I.3.1(c).]*

I.3.1.1 Full transverse systems are equipped with supply and exhaust air ducts throughout the length of the tunnel roadway *[see Figure I.3.1(a)]*. When a full transverse system is deployed, the majority of the pollutants or smoke discharges through a stack or stacks, with a minor portion of the pollutants or smoke exiting through the portals. A full transverse ventilation system can be either balanced (exhaust equals supply) or unbalanced (exhaust is greater than supply).

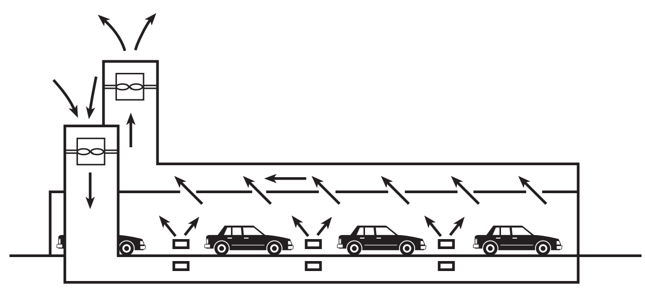

FIGURE I.3.1(a) Full Transverse Ventilation System.

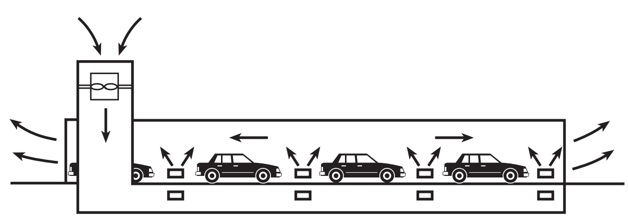

FIGURE I.3.1(b) Semitransverse Supply Ventilation System.

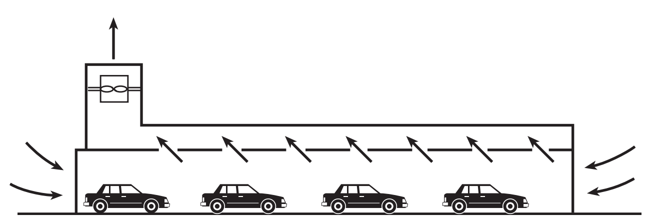

FIGURE I.3.1(c) Semitransverse Exhaust Ventilation System.