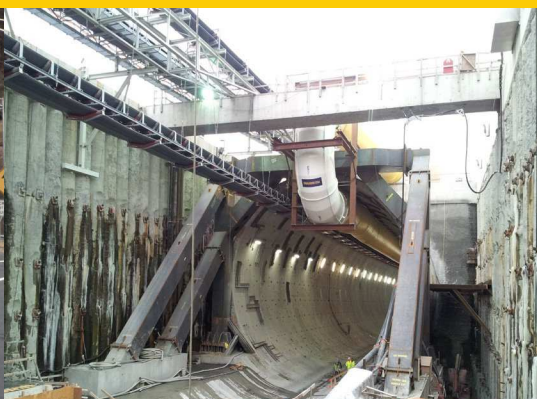




LRFD Road Tunnel Design and Construction Guide Specifications

First Edition, 2017

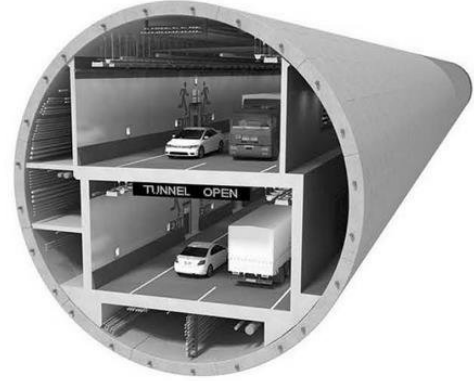


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AASHTO LRFD Road Tunnel Design and Construction Guide Specifications

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SECTION 1 – INTRODUCTION

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1.1—PURPOSE AND SCOPE

The provisions of these Specifications are intended for the design, evaluation, and rehabilitation of highway tunnels. These Specifications are intended for the design of tunnels constructed using cut-and-cover, bored, mined, and immersed tunnel construction methodologies.

Provisions are not included in these Specifications for water conveyance, utility, transit, or rail tunnels or for shafts. For tunnel elements not explicitly covered herein, the provisions of these Specifications may be applied, as augmented by the Engineer with additional design criteria where required.

Construction specifications consistent with these design Specifications are not included. There is a listing of suggested construction specification sections included in Appendix B.

Structures internal to tunnels that support roadways over ventilation plenums, roadways, or other openings in the tunnel shall be designed in accordance with the *AASHTO LRFD Bridge Design Specifications* (hereafter referred to as the *LRFD Specifications*) including all applicable interim changes and as modified or supplemented herein. The load effects of these internal structures shall be applied to the tunnel lining, walls, or other supporting members in accordance with these Specifications.

Retaining walls for retained cut approaches to tunnels shall be designed in accordance with the *LRFD Specifications*.

Support and ancillary structures such as ventilation, control, and administrative buildings are not covered by these Specifications. These structures shall be designed in accordance with local building codes.

These Specifications are not intended to supplant proper training and experience or the exercise of judgment by the Engineer, and provide only the minimum requirements necessary for public safety. The Owner or the Engineer may require the sophistication of design or the quality of materials and construction to be higher than the minimum requirements. The design of tunnels is strongly dependent upon the geologic setting, site conditions, and construction methodology, and this fact is considered in the Specifications. The concept of ground/structure interaction is emphasized for mined and bored tunnels; however, it is also applicable to cut-and-cover and immersed tunnels.

The concept of safety through redundancy and ductility is emphasized for tunnel elements subject to repeated loads and load reversals.

The design provisions of these Specifications employ the Load and Resistance Factor Design (LRFD) methodology. The load factors have been calibrated using structural analysis modeling for a limited number of loading conditions that take into account ground/structure interaction.

C1.1

These Specifications are modeled after the *LRFD Specifications* and the *AASHTO Guide Specifications for LRFD Seismic Bridge Design*. The philosophy and guidance provided in those documents are carried forward and implemented in this document.

Whenever the *LRFD Specifications* are referenced in this document, the reference is to the latest edition including all applicable interim changes.

The term “notional” is often used in these Specifications to indicate an idealization of a physical phenomenon, as in “notional load” or “notional resistance.” Use of this term strengthens the separation of an engineer’s “notion” or perception of the physical world in the context of design from physical reality itself.

The term “shall” denotes a requirement for compliance with these Specifications.

The term “should” indicates a strong preference for a given criterion.

The term “may” indicates a criterion that is usable, but other local and suitably documented, verified, and approved criteria may also be used in a manner consistent with the LRFD approach to tunnel design.

The load factors specified in Section 3 have been calibrated to provide designs with member proportions consistent with the current practice in tunnel design.

The calibration is based upon analyses performed for a circular bored tunnel. Additional calibration for different tunnel cross-sectional geometry and loadings from a variety of ground conditions would be useful in further validating and refining the load factors.

The primary loads on structural components of tunnels are groundwater and earth loads. For immersed tunnels, loads imposed by transporting immersed elements from the fabrication site to the tunnel location can also govern the design of these tunnels. For pre-fabricated linings used in bored tunnels, construction-imposed loading can govern the design. The determination of groundwater, earth, transportation, and other construction loads varies based on the in-situ conditions, level of testing during subsurface investigations, and ground conditions may have great variation. There are little data available to establish a statistically significant sampling in order to calibrate these Specifications based upon structural reliability theory. As such, judgment and past experience were also used to select the load factors.

These Specifications are an initial attempt to codify and standardize highway tunnel design. As such, as future data that are produced in a systematic fashion in accordance with these Specifications become available, recalibration may be implemented based on statistical evaluation of these data.

The commentary is not intended to provide a complete historical background concerning the development of these Specifications, nor is it intended to provide a detailed summary of the studies and research data reviewed in formulating the provisions of the Specifications. However, references to some of the research data are provided for those who wish to study the background material in more depth.

The commentary directs attention to other documents that provide suggestions for carrying out the requirements and intent of these Specifications. However, those documents and this commentary are not intended to be a part of these Specifications.

The Specifications direct the Engineer to utilize other documents in the development of designs. When this occurs, the most current edition of those documents should be utilized. Those documents referenced in the Specifications are intended to be part of these Specifications by reference.

Unless otherwise specified, the Materials Specifications referenced herein are the *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing*.

1.2—DEFINITIONS

For definitions not shown, see the *LRFD Specifications*.

Bored Tunnel—A tunnel constructed utilizing a tunnel boring machine.

Calibration—The selection of load and resistance factors to achieve a specified goal such as uniform reliability, as is the case with the bridge design specifications, or member proportions consistent with past practice, as is the case with these Specifications.

Collapse—A major change in the geometry of the tunnel lining or other structural component rendering it unfit for use.

Component—Either a discrete element of the tunnel or a combination of elements requiring individual design consideration.

Contract Documents—Drawings, specifications, reports, and memoranda that provide direction and/or guidance for the construction of a tunnel and that form a contractual basis for the work to be performed.

Contractor—Entity responsible for the construction of the tunnel and associated construction engineering.

Cut-and-cover—Sequence of construction in which a trench is excavated and the tunnel or conduit section is constructed and then covered with backfill. (AASHTO, 2010)

Design—Proportioning and detailing the components and connections of a tunnel.

Design Life—Period of time on which the statistical derivation of transient loads is based: 150 years for these Specifications.

Engineer—Agency, design firm, or person responsible for the design of the tunnel and/or review of design related to field submittals.

Evaluation—Determination of the load carrying capacity of one or more components of an existing tunnel.

Extreme Event Limit States—Limit states relating to events such as earthquakes, flooding, vehicle fire, or vehicle and vessel collision, with return periods in excess of the design life of the tunnel.

Force Effect—A deformation, stress, or stress resultant (i.e., axial force, shear force, torsional or flexural moment) caused by applied loads, imposed deformations, temperature changes, or volumetric changes.

Immersed Tunnel—A tunnel constructed from prefabricated elements constructed off the tunnel alignment, floated into place over the tunnel alignment, and placed into a prepared trench. Placement is facilitated by the addition of ballast to the elements to cause them to be immersed to the pre-determined depth and then joined to the adjacent element(s) already in place.

Limit State—A condition beyond which the tunnel or component ceases to satisfy the provisions for which it was designed.

Load Modifier—A factor accounting for ductility, redundancy, and the operational classification of the tunnel.

Mined—Any tunnel construction methodology that involves excavation of the tunnel without opening the excavation to the surface and without the use of a tunnel boring machine, including mechanical excavation, blasting, and hand excavation.

Model—An idealization of a structure or structure-ground system for the purpose of analysis.

Owner—Person or agency having jurisdiction over the tunnel.

Regular Service—Condition excluding the presence of special permit vehicles and extreme events.

Rehabilitation—A process in which the resistance or functionality of a tunnel component or connection is either restored or increased.

Resistance Factor—A statistically or experience-based multiplier applied to nominal resistance accounting primarily for variability of material properties, structural dimensions, and workmanship, an uncertainty in the prediction of resistance, but also related to the statistics of the loads through the calibration process.

Service Life—The period of time that the tunnel is expected to be in operation.

Tunnel—Road tunnels as defined by the American Association of State Highway and Transportation Officials (AASHTO) Technical Committee for Tunnels (T-20) are enclosed roadways with vehicle access that is restricted to portals regardless of type of the structure or method of construction. The committee further defines road tunnels not to include enclosed roadway created by highway bridges, railroad bridges, or other bridges. This definition applies to all types of tunnel structures and tunneling methods such as cut-and-cover tunnels, mined and bored tunnels in rock and soft ground, and immersed tunnels.

Tunnel Boring Machine (TBM)—Machine that excavates a tunnel by drilling out the heading to full size in one operation. Sometimes called a mole, the TBM is typically propelled forward by jacking off the excavation supports emplaced behind it or by gripping the side of the excavation (AASHTO, 2010).

1.3—DESIGN PHILOSOPHY

1.3.1—General

Tunnels shall be designed for specified limit states to achieve the objectives of constructability, safety, and serviceability, with due regard to issues of inspectability, maintenance and economy. Additional information regarding tunnel systems, planning, ancillary facilities, and appurtenances can be found in Section 2. Regardless of the type of analysis used, Equation 1.3.2.1-1 shall be satisfied for all specified force effects and combinations thereof.

C1.3.1

The limit states specified herein are intended to provide for a buildable, serviceable tunnel capable of safely operating for a specified design life. As defined in Article 1.2, the design life relates to the return period of the transient loads of the strength limit states and hence their nominal magnitude. The design life should not be confused with the service life. As defined in Article 1.2, the service life relates to the overall demonstrated durability of the tunnel. The service life of

The specified 150-year design life is appropriate for the design of tunnel geotechnical features and soil-structure-interaction-systems given the high capital costs of rehabilitation and replacement and the likely importance to the transportation network. Internal structures such as roadway slabs and suspended ceilings as well as system components, such as signs, piping, and their supports; communication and signal devices; and ventilation equipment that are more easily replaced, may have design lives assigned to them by the Owner.

a tunnel is not specified in these Specifications, just as the service life of a bridge is not specified in the *LRFD Specifications*, as the durability of tunnels or bridges is not well quantified.

The resistance of components and connections is determined, in many cases, on the basis of inelastic behavior. In other words, the capacity of tunnel components used to define their nominal resistance at the strength limit states is based upon behavior past first yield of the material. On the other hand, the force effects on the load side of the LRFD equation, Equation 1.3.2.1-1, are determined using elastic analysis but amplified by the specified load factors. This apparent inconsistency is consistent with most modern structural-design codes including the *LRFD Specifications*. The application of this comparison of loads and resistances for design is a result of incomplete knowledge of inelastic structural action combined with the behavior of the earth surrounding the tunnel that acts in concert with the tunnel structure.

1.3.2—Limit States

1.3.2.1—General

Each component and connection shall satisfy Equation 1.3.2.1-1, for each limit state unless otherwise specified. For service and extreme limit states, resistance factors shall be taken as 1.0 except for bolts. For bolts, the provisions of Article 6.5.5 of the *LRFD Specifications* shall apply.

$$\sum \eta_i \gamma_i Q_i \leq \phi R_n = R_r \quad (1.3.2.1-1)$$

in which:

For loads for which a maximum value of γ_i is appropriate:

$$\eta_i = \eta_D \eta_R \eta_I \geq 1.0 \quad (1.3.2.1-2)$$

For loads for which a minimum value of γ_i is appropriate:

$$\eta_i = \frac{1}{\eta_D \eta_R \eta_I} \leq 1.0 \quad (1.3.2.1-3)$$

where:

γ_i = load factor: a multiplier applied to force effects

ϕ = resistance factor: a multiplier applied to nominal resistance, as specified herein

η_i = load modifier: a factor relating to ductility, redundancy, and operational classification

CI.3.2.1

Equation 1.3.2.1-1 is the basis of the LRFD methodology.

Ductility, redundancy, and operational classification are considered in the load modifier η . Whereas the ductility and redundancy directly relate to physical strength, operational classification concerns the consequences of the tunnel being out of service. The grouping of these aspects of the load side of Equation 1.3.2.1-1 is therefore, arbitrary. However, it constitutes a first effort at codification. In the absence of more precise information, each effect is estimated as ± 5 percent, accumulated geometrically, a clearly subjective approach.

Groundwater is an example of a loading that would be appropriate to apply as a maximum and a minimum. Variation in groundwater elevations are common due to seasonal changes and tidal influences. Tunnel linings are designed as compression members; therefore, maximum groundwater pressures would produce maximum axial loads and vice versa. As such, both maximum and minimum groundwater loads should be checked.

η_D = a factor relating to ductility as specified in Article 1.3.3

η_R = a factor relating to redundancy as specified in Article 1.3.4

η_I = a factor relating to operational classification as specified in Article 1.3.5

Q_i = force effect

R_n = nominal resistance

R_r = factored resistance: ϕR_n

1.3.2.2—Service Limit State

The service limit state shall be taken as restrictions on stress, deformation and crack width under regular service conditions.

CI.3.2.2

The service limit state provides certain experience-related provisions that cannot always be derived solely from strength or statistical consideration.

For tunnels, this limit state controls tunnel lining deformation, cracking, and leaking.

1.3.2.3—Fatigue and Fracture Limit State

The fatigue and fracture limit state shall be taken as restrictions on stress range as a result of repetitive machinery or ventilation loads at the number of expected stress range cycles.

CI.3.2.3

The fatigue and fracture limit state is intended to limit crack growth under repetitive loads to prevent fracture during the design life of the component. Additionally, the fatigue limit state is intended to prevent premature failure of anchoring and supporting components subject to machinery or ventilation loads.

1.3.2.4—Strength Limit State

Strength limit state shall be taken to ensure that strength and stability, both local and global, are provided to resist the specified statistically significant load combinations that a tunnel and its component parts are expected to experience in its design life.

CI.3.2.4

The strength limit state considers stability or yielding of each structural element. If the resistance of any element, including splices and connections, is exceeded, it is assumed that the tunnel resistance has been exceeded. The redistribution of loads that can occur due to structure-ground interaction typically allows the tunnel ground supporting structure to support loads in excess of the capacity calculated utilizing linear elastic static analysis. Extensive distress and structural damage may occur under the strength limit state, but overall structural integrity is expected to be maintained.

1.3.2.5—Extreme Event Limit State

The extreme event limit state shall be taken to ensure the structural survival of a tunnel during a major earthquake, flood, tsunami, collision, blast, or fire, or when an immersed tunnel is subject to sinking vessel or anchor drag loads possibly during, or in conjunction with, a scour event.

CI.3.2.5

Extreme event limit states are considered to be unique occurrences whose return period may be significantly greater than the design life of the tunnel.

1.3.3—Ductility

The structural system of a tunnel shall be proportioned and detailed to ensure the development of

C1.3.3

The response of structural components or connections beyond the elastic limit can be

significant and visible inelastic deformations at the strength and extreme limit states before failure.

For the strength limit state:

$\eta_D \geq 1.05$ for nonductile components and connections

= 1.00 for conventional designs and details complying with these Specifications

For all other limit states:

$\eta_D \geq 1.00$

Internal components of tunnels including structural elements, equipment supports, and their connections shall be designed to exhibit ductile behavior, especially when subject to extreme events such as earthquakes.

Attention shall be given to the ductility of transitions between structural systems of tunnels, specifically at the interfaces between retained cut and cut-and-cover structures; between cut-and-cover structures and mined, bored, or immersed tunnels; and at the joints between immersed tunnel elements.

1.3.4—Redundancy

The provisions of the *LRFD Specifications* shall be used to ensure that the internal components of tunnels and all aspects of cut-and-cover and immersed tunnels incorporate redundancy in their design.

For the strength limit state:

$\eta_R \geq 1.05$ for nonredundant members

= 1.00 for conventional levels of redundancy

For all other limit states:

$\eta_R \geq 1.00$

1.3.5—Operational Importance

This Article shall apply to the strength and extreme limit states only.

The Owner may declare a tunnel or any structural component, or connection thereof, to be of operational priority.

For the strength limit state:

$\eta_I \geq 1.05$ for critical or essential tunnels

= 1.00 for typical and relatively less important tunnels

For all other limit states:

$\eta_I \geq 1.00$

characterized by either brittle or ductile behavior. Brittle behavior is undesirable because it implies a sudden loss of load-carrying capacity immediately when the elastic limit is reached. Ductile behavior is characterized by significant inelastic deformations before any loss of load carrying capacity occurs. The redistribution of load effects provided by ground–structure interaction results in ductile behavior of concrete tunnel linings when proper detailing of the reinforcing is used. Internal components, however, should be designed to exhibit ductile behavior. The provisions of the *LRFD Specifications* provide guidance and direction for the ductile design of these internal components.

While the *LRFD Specifications* have a value of η_D less than one in implementation, the value is unused. Traditionally, structural engineers characterize structures as ductile, $\eta_D = 1.00$, or non-ductile, $\eta_D = 1.05$.

C1.3.4

Tunnel linings for bored and mined tunnels are considered redundant due to ground–structure interaction and the ability to share load along the length of tunnel.

While the *LRFD Specifications* include a value of η_R less than one, in implementation the value is unused. Traditionally, structural engineers characterize structures as redundant, $\eta_R = 1.00$, or non-redundant, $\eta_R = 1.05$.

C1.3.5

Such classification should be done by personnel responsible for the affected transportation network and knowledgeable of its operational needs. The definition of operational priority may differ from Owner to Owner. Guidelines for classifying critical or essential tunnels are as follows:

- Tunnels that are required to be open to all traffic once inspected after the design event and are usable by emergency vehicles and for security, defense, economic, or secondary life safety purposes immediately after the design event.
- Tunnels that should, as a minimum, be open to emergency vehicles and for security, defense, or

economic purposes after the design event, and open to all traffic within days after that event.

Owner classified tunnels may use a value of $\eta < 1.0$ based on ADTT, available detour length, or other rationale to use less stringent criteria.

1.4—REFERENCES

1. AASHTO. *LRFD Bridge Design Specifications*. 7th ed. American Association of State Highway and Transportation Officials, Washington, DC, 2014.
2. AASHTO. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*. American Association of State Highway and Transportation Officials, Washington, DC, 2016.
3. AASHTO. *Technical Manual for Design of Road Tunnels—Civil Elements*. American Association of State Highway and Transportation Officials, Washington, DC, 2010.

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2.1—SCOPE

Design provisions for road tunnel structures herein are categorized in terms of the construction methodology used. Minimum requirements are provided for:

- Clearances
- Environmental protection
- Planning
- Aesthetics of tunnel portals
- Economy
- Rideability
- Durability
- Constructability
- Inspectability
- Maintainability
- User safety

Minimum requirements for tunnel systems are specified with references to source documents.

2.2—DEFINITIONS

For definitions not shown, see the *LRFD Specifications*.

Authority Having Jurisdiction (AHJ)—Office or person charged with enforcing the life-safety code for the tunnel.

Bore—Tunnel construction methodology that employs the use of a Tunnel Boring Machine (TBM).

Construction Portal—The location of the start of mining or boring operations. This location often adjoins a cut-and-cover section of tunnel that connects to the permanent portal.

Cross Passage—Passageway constructed between two adjacent tunnels to provide access between the tunnels.

Crown—The highest point of the tunnel lining.

Cutter Head—The front end of a mechanical excavator, usually a wheel on a tunnel boring machine that cuts through rock or soft ground. (AASHTO, 2010)

Element—Pre-fabricated section of an immersed tunnel that is joined with adjacent sections to construct the tunnel.

Face—The ground exposed at the head of the tunnel when tunnel construction is performed by mining or boring.

Invert—On a circular tunnel, the invert is approximately the bottom 90 degrees of the arc of the tunnel; on a square-bottom tunnel, it is the bottom of the tunnel. (AASHTO, 2010)

Lagging—Wood planking, steel channels, or other structural materials spanning the area between ribs.

Liner Plates—Pressed steel plates installed between the webs of the ribs to make a tight lagging, or bolted together outside the ribs to make a continuous skin. (AASHTO, 2010)

Lining—Structural system constructed in intimate contact with the ground, used to stabilize the tunnel opening and to support hydrostatic loads.

C2.1

This section provides the Engineer with information to determine the overall configuration of the tunnel. The tunnel configuration must accommodate the vehicles permitted to use the tunnel while providing a safe environment for the travelling public during normal and extreme operating conditions.

Mixed Face—The situation when the tunnel passes through two (or more) materials of markedly different characteristics and both are exposed simultaneously at the face (e.g., rock and soil, or clay and sand).

Muck—The ground excavated during tunnel construction.

Permanent Portal—The location where vehicle traffic enters the tunnel during normal operation of the tunnel.

Rib—1. An arched individual frame, usually of steel, used in tunnels to support the excavation; also used to designate the side of a tunnel. 2. An H- or I-beam steel support for a tunnel excavation. (AASHTO, 2010)

Segmental Lining—Tunnel lining constructed from segments that make up a ring of support; commonly steel or precast concrete.

Segments—Sections that make up a ring of support or lining of a mined or bored tunnel; commonly steel or precast concrete.

Sequential Excavation Method—Construction methodology in which the tunnel is mined in specified sequence to control ground movements; also known as the New Austrian or North American Tunneling Method (NATM).

Springline—The point where the curved portion of the roof meets the top of the wall. In a circular tunnel, the springlines are at opposite ends of the horizontal center line. (AASHTO, 2010)

2.3—NOTATION

2.3.1—General

cd/m^2	=	candelas per square meter (2.8.5.1.1) (C2.8.5.1.3)
fc	=	foot candle (2.8.5.2)
ft	=	foot (2.8.5.3) (2.8.6.5.3) (2.8.6.5.4)
hr	=	hour (2.8.3)
L_{seq}	=	equivalent veiling luminance (2.8.5.1.1) (C2.8.5.1.1)
$MBtu/hr$	=	Mega (1 million) British thermal units per hour (2.8.3)
mph	=	miles per hour (2.8.3.1) (2.8.11.2)
MW	=	Megawatt (1 million Watts) (2.8.3)
ppm	=	parts per million (2.8.3.2)

2.3.2—Abbreviations

<i>ACS:</i>	Access control system
<i>AI:</i>	Analog input
<i>AMCA:</i>	Air Movement and Control Association International, Inc.
<i>ANSI:</i>	American National Standard Institute
<i>ASHRAE:</i>	American Society of Heating, Refrigerating and Air-Conditioning Engineers
<i>ASTM:</i>	ASTM International, formerly known as American Society for Testing and Materials
<i>AWG:</i>	American wire gauge
<i>CEI:</i>	International Commission on Illumination
<i>CFD:</i>	Computational fluid dynamics
<i>CO:</i>	Carbon monoxide
<i>DC:</i>	Direct current
<i>DI:</i>	Digital input
<i>DMS:</i>	Dynamic message signs
<i>DO:</i>	Digital output
<i>EIS:</i>	Environmental Impact Statement

<i>EPA:</i>	Environmental Protection Agency
<i>FEIS:</i>	Final Environmental Impact Statement
<i>FHWA:</i>	Federal Highway Administration
<i>FONSI:</i>	Finding of No Significant Impact
<i>HMI:</i>	Human operator interfaces
<i>ICC:</i>	International Code Council
<i>IDS:</i>	Intrusion detection system
<i>IEEE:</i>	Institute of Electrical and Electronic Engineers
<i>IES:</i>	Illuminating Engineering Society
<i>I/O:</i>	Input/output
<i>ITA:</i>	International Tunneling Association
<i>LED:</i>	Light emitting diode
<i>LLF:</i>	Light loss factors
<i>LUS:</i>	Lane use signals
<i>NATM:</i>	New Austrian or North American Tunneling Method
<i>NEMA:</i>	National Electrical Manufacturer's Association
<i>NEPA:</i>	National Environmental Policy Act
<i>NFPA:</i>	National Fire Protection Association
<i>NIOSH:</i>	National Institute for Occupational Safety and Health
<i>NO:</i>	Nitric oxide
<i>NO₂:</i>	Nitrogen dioxide
<i>NO_x:</i>	Oxides of nitrogen
<i>PIARC:</i>	World Road Association
<i>PLC:</i>	Programmable logic controller
<i>PTZ:</i>	Pan, tilt, zoom
<i>RIO:</i>	Remote input/output
<i>ROD:</i>	Record of decision
<i>SCADA:</i>	Supervisory control and data acquisition
<i>SSSD:</i>	Safe sight stopping distance
<i>TBM:</i>	Tunnel boring machine
<i>TSCS:</i>	Traffic surveillance and control system
<i>TVCS:</i>	Tunnel ventilation control system
<i>TVS:</i>	Tunnel ventilation system
<i>TWA:</i>	Time weighted average
<i>UL:</i>	Underwriters Laboratory
<i>UPS:</i>	Uninterruptable power supply
<i>USACE:</i>	United States Army Corps of Engineers

2.4—TYPES OF ROAD TUNNEL STRUCTURES

C2.4

The tunnel structure types herein are defined by the methodology used to construct the tunnel. A tunnel type study should be conducted as part of the planning phase of the tunnel to determine the most appropriate construction methodology to be used.

The construction methodology is dictated by:

- ground conditions
- road typical section
- economics
- environment and available land surrounding the portals
- risk

Materials for the structural components inside the tunnel vary and are dictated by economics as well as the construction methodology. Additional information



regarding tunnel type studies can be found in AASHTO's *Technical Manual for Design and Construction of Road Tunnels—Civil Elements*.

2.4.1—Cut-and-Cover Tunnels

Cut-and-cover tunnels are defined as those constructed by excavating a trench, constructing a concrete structure to create the tunnel opening in the trench, and covering it with soil. The concrete tunnel structure may be cast-in-place or constructed from precast elements. Detailed design requirements for this type of tunnel are provided in Section 6.

2.4.2—Mined Tunnels

Mined tunnels are defined as those constructed utilizing mechanical excavating equipment or blasting without disturbing the ground surface. The choice of mechanical excavating equipment or blasting is dependent on the ground conditions being excavated. The shape of the excavation is customized to the ground conditions and geometric functional requirements of the tunnel. The excavated ground typically requires initial support prior to the construction of a permanent lining. Mined tunnels in competent rock may also be unlined. Detailed design requirements for this type of tunnel are provided in Section 7.

2.4.3—Bored Tunnels

Bored tunnels are defined as those constructed through the use of specialized equipment known as tunnel boring machines (TBMs) without disturbing the ground surface. The excavation process may be performed in free air or may require a pressurized face depending on ground and groundwater conditions. A bored tunnel may be unlined or lined. Detailed design requirements for this type of tunnel are provided in Section 7.

2.4.4—Immersed Tunnels

Immersed tunnels are defined as those constructed by immersing a prefabricated element into a prepared trench excavated from the bottom of a waterway. Immersed tunnels are a specialized type of cut-and-cover tunnel. Pre-fabricated tunnel elements are constructed of precast-concrete or a combination of structural steel and concrete, sealed with bulkheads at each end, and floated from the fabrication yard to the construction site. The elements are located over the excavated trench and lowered into place by adding ballast. Once in place, the elements are

C2.4.1

Cut-and-cover construction may be utilized for the entire length of the tunnel or only a portion of the tunnel. Cut-and-cover methodology may be required when constructing a tunnel using mined or bored methodologies. The cut-and-cover portion of the tunnel is utilized to bring the tunnel alignment to the depth required to initiate the mined or bored construction activities.

C2.4.2

Jacked box tunnels are included in the category of mined tunnels. Jacked box tunnels are prefabricated box structures jacked horizontally through the ground using methods to reduce the friction between the ground and the box. Jacked box tunnels often are used where the tunnel is required to be very shallow and it is not possible to disturb the surface, for example beneath active runways at airports or under railway embankments.

Mined tunnels include those constructed utilizing the sequential excavation method.

Mined tunnels may be constructed in free air or under compressed air.

C2.4.3

The TBM consists of a shield to temporarily support the ground, a cutter head for excavating the ground and removing the muck, and supporting equipment.

TBMs utilized for rock tunneling may include gripper pads to provide forward thrust for the TBM. TBMs for soft ground and some rock tunnels may include an array of jacks to provide forward thrust for the TBM.

C2.4.4

Although immersed tunnels are a subset of cut-and-cover tunnels, the portion of the tunnel that is submerged under water is referred to as the immersed tunnel. The tunnel alignment must transition on land from the depth where the tunnel element can be submerged to the depth where a retained cut can be constructed. This transition is constructed utilizing cut-and-cover technology as described in Article 2.4.1. This transition is referred to as the cut-and-cover portion of the tunnel.

connected to adjoining sections and backfilled. Detailed design requirements for this type of tunnel are provided in Section 8.

2.4.5—Shafts

Shafts are defined as vertical or steeply inclined excavations that connect the tunnel to the ground surface, and are located between the tunnel portals. Shafts may be excavated from the surface or from underground back to the surface. Shafts are not addressed in this specification.

2.5—PLANNING AND ROUTE CONSIDERATIONS

2.5.1—General

The selection of the type of tunnel shall be based on the geometrical configurations, ground conditions, type of crossing, and environmental requirements.

The choice for location of tunnels shall be supported by analyses of alternatives, which is typically completed during the planning and National Environmental Policy Act (NEPA) phase of tunnel projects. The Preferred Alternative is typically identified in the final NEPA decision document (e.g., Final Environmental Impact Statement (FEIS)/Record of Decision (ROD), Finding of No Significant Impact (FONSI)) as the final approved location for the alignment.

Immersed tunnel elements must be designed to resist the load effects associated with floating at the fabrication site and transportation to the construction site.

C2.4.5

Shafts are typically used for emergency egress and ventilation when required by the length of the tunnel.

C2.5.1

There are multiple components to vehicular transportation systems, including surface roads, bridges, viaducts, and tunnels. The selection of a road tunnel over other components for a project (or a portion of a project) is typically determined prior to the design phase. Road tunnels are often selected to shorten travel times and distance, avoid surface traffic congestion or surface disturbance, or to cross physical barriers such as mountains, rivers, or other water bodies.

Tunnel planning is typically subject to NEPA, 42 U.S.C. 4321–4347, since most tunnel projects likely involve federal funding or federal approval, triggering NEPA. For roadway tunnels involving federal funding, the following NEPA regulations are applicable:

- 40 CFR Part 1500-1508, CEQ Regulations for Implementing NEPA
- 23 CFR 771, FHWA, Environmental Impacts and Related Procedures

NEPA requires the evaluation of alternatives during the planning phase, and a Preferred Alternative is selected at the conclusion of the NEPA process. The Preferred Alternative is identified in the final NEPA decision document (e.g., FEIS/ROD, FONSI), identifying the final approved location for the alignment. The NEPA document outlines the purpose and need that the proposed project is intended to address, including an evaluation of the effectiveness of the Preferred Alternative in meeting the identified purpose and need for the project. All of this planning level work is completed early during the planning/NEPA process such that it does not have to be completed separately as part of the tunnel final design phase. There are requirements for a NEPA re-evaluation or supplemental document related to design changes or time elapsed since last NEPA approval, but for the purposes of this design manual, it will be assumed that projects receive NEPA approval, including the general location for the tunnel alignment.

During the design phase, the Engineer shall adhere to the final NEPA decision document regarding compliance with relevant environmental requirements related to the project, including design commitments, mitigation commitments, or other commitments that were agreed to be considered or implemented during the design phase of the project. Any proposed changes to the Preferred Alternative shall be evaluated in accordance with 23 CFR Sections 771.129 and 771.130, and shall be approved by the lead federal agency before the agency may proceed with the change.

As the design advances beyond the NEPA phase, attention shall continue to be directed toward providing for a favorable tunnel design that:

- Minimizes environmental effects (natural, social, and cultural resources);
- Facilitates practical, cost effective design, construction, operation, inspection, and maintenance;
- Provides for the desired level of service and safety;
- Minimizes adverse impacts to other existing infrastructure; and
- Adheres to and implements design-related NEPA requirements in accordance with the final NEPA decision document.

Additional information regarding planning and route considerations can be found in Appendix A.

2.6—DESIGN CONSIDERATIONS FOR INSPECTION AND MAINTENANCE

Because so much planning goes into the selection of the Preferred Alternative, the general tunnel alignment is typically determined prior to final design efforts. The NEPA document typically summarizes planning studies carried out prior to NEPA, the scoping process, the development process and screening of alternatives, and the evaluation of alternatives carried forward for detailed study in the NEPA document.

When federal funding is not anticipated for a project, local requirements should be followed for the planning process.

During the NEPA process, the selection of the approved alignment will have fully evaluated the environmental consequences of the project, including natural, social, and cultural resources, as well as land use, economic, engineering, future planning, and cost considerations. The NEPA phase will have also considered and documented public and agency comments related to the tunnel location and alignment.

C2.6

The design of tunnels shall be performed in a manner that considers future operation and maintenance needs as well as the need to inspect the facility. Care shall be taken to design and detail components and systems for ease of maintenance and inspection. The following guidelines shall be used to meet this requirement.

- Areas that are defined as confined space during any non-emergency operating mode of the tunnel by any regulatory entity within the jurisdiction within which the tunnel resides should be avoided.
- Access to and egress from spaces such as air plenums above and below the roadway

should be provided through pathways that can be used when traffic is present in the tunnel.

- Tunnel systems and systems components, including connections and attachments thereof, shall be accessible for inspection and maintenance and shall not be concealed behind architectural finishes or other tunnel components that are not easily removed.
- Tunnel systems conduits should not be embedded inside structural walls or slabs nor buried in the tunnel backfill or overburden.
- Penetrations of exterior tunnel structural walls and lining for passage of utility systems conduits should be avoided.
- Systems devices (lighting fixtures, signs, signals, smoke alarms, antennae, etc.) should be designed and detailed to withstand the effects of tunnel washing.
- Systems devices should be located in areas where safe access is possible when traffic is present inside the tunnel.
- Drainage systems should be designed and detailed to be inspectable and maintainable. Consideration should be given to site-specific groundwater conditions that could affect the long-term performance of the drainage system.

In some situations, this requirement cannot be met. For example, in mined tunnels with no ventilation plenum under the roadway, drainage systems will have to be buried in the ground beneath the roadway. Creating accessible space for systems constructed below the roadway could be prohibitively expensive. Local code requirements should also be adhered to when locating systems conduit.

If economically feasible, systems devices may be able to be located over shoulders that can be closed for access to the device for maintenance or replacement. Devices that must be located over traffic lanes will require lane closures for access.

2.7—CLEARANCE AND GEOMETRIC REQUIREMENTS

Minimum roadway clearance and geometric requirements shall be taken from the latest edition of AASHTO's *A Policy on Geometric Design of Highways and Streets* (hereafter referred to as the *Green Book*). Additional guidance is provided in the following articles.

Clearances to obstacles in the tunnel shall be determined from a dynamic vehicle envelope established from the vehicles anticipated to use the tunnel. The dynamic vehicle envelope shall account for the static envelop plus dynamic behavior such as bouncing, suspension failure, vehicle overhang on curves and lateral movement due to operational characteristics, and driver error. The dynamic envelope shall be applied to all areas where a vehicle can travel, including shoulders and emergency walkways.

C2.7

The requirements of this article are intended to provide a safe travel environment inside the tunnel without imposing undue expense on tunnel owners. Information on existing tunnel shoulder and walkways can be found in NCHRP Project 20-68A Scan 09-05, *Best Practices for Roadway Tunnel Design, Construction, Maintenance and Operations*, April, 2011.

Obstacles in the tunnel include the tunnel structure, signs, signals, light fixtures, antennae, ventilation, and firefighting equipment, doors in the open position when opening into the roadway, curbs, walkways, railings, etc.

2.7.1—Vertical Clearances

The minimum vertical clearance for tunnels shall be 16 feet, unless otherwise specified by the Owner.

The minimum vertical clearance for any tunnel shall not be less than that permitted on the facility leading to the tunnel.

2.7.2—Horizontal Clearances

Obstacles shall not encroach on the vehicle dynamic envelope.

The minimum travel lane width shall be 12 feet. The minimum width of roadway in any tunnel shall be the approach roadway travel lane(s) pavement width plus two feet.

2.7.3—Shoulders and Walkways

When required for safety or when economically feasible, shoulders shall be provided in accordance with the *Green Book*.

A minimum walkway width of 3'-6" shall be provided outside the shoulders or, when no shoulders are present, outside the roadway. The walkway shall be raised above the roadway by a minimum of six inches.

The requirements of NFPA 502 shall be considered when dimensioning shoulders and walkways.

2.7.4—Vertical Alignment

Vertical curves shall be in accordance with the *Green Book*.

The preferred maximum grade is four percent; however, the absolute maximum grade shall be six percent.

2.7.5—Horizontal Alignment

The tunnel horizontal alignment shall be as short as practical and maintain as much of the alignment on tangent as practical. When required, horizontal curves shall be in accordance with the *Green Book* except as noted below.

When designing horizontal curves, the limitations of the tunneling methodology used to construct the tunnel shall be considered. Consultation with TBM manufacturers shall be included in the preliminary

C2.7.3

When the egress walkway is raised more than six inches above the roadway, consideration should also be given to providing general access to the walkway from the roadway to assist motorists in accessing the walkway during a tunnel evacuation.

C2.7.4

When designing the vertical alignment, consideration should be given to the operational characteristics of the vehicles using the tunnel, the average daily truck traffic, and the effect on traffic flow of steep grades.

Consideration should also be given to the demands on the tunnel ventilation system (TVS) generated by vehicles negotiating steep grades and the need to drain the roadway.

C2.7.5

Maintaining a tangent through as much of the tunnel as practical will result in the shortest tunnel with the accompanying effect of reducing the cost of the tunnel.

Cut-and-cover and mined tunnels can be built to any roadway geometry, but bored tunnels are restricted to the performance characteristics of the tunnel boring machine used to excavate the tunnel. TBMs are not

engineering phases of a bored tunnel to ensure that the horizontal alignment can be constructed.

When chorded construction is used for tunnel walls where alignments are curved, chord lengths shall be determined to meet sight distance requirements in accordance with the *Green Book*.

Sight distance inside the tunnel shall be checked to verify that the design speed is consistent with the curve radii including the fact that the tunnel walls are obstructions to stopping sight distance.

2.7.6—Tunnel Approaches

The retained cuts at the tunnel approaches shall have as a minimum the same horizontal clearances as the inside of the tunnel.

Vertical alignments shall be established to provide a positive means of protection against flooding when tunnel portals are located in low-lying areas. If it is impractical to establish an alignment that will preclude flooding, then other positive flood protection measures shall be incorporated into the design.

Tunnel approaches shall be equipped with over-height warning devices to alert drivers that are operating a vehicle that is too tall to enter the tunnel. The warning devices shall provide visible means of alerting the driver that include a text warning and flashing yellow lights.

The over-height warning devices shall be located prior to an alternate route and shall provide directions to the alternate route. When it is not practical or useful to locate the over-height warning devices prior to an alternate route, a means to turn over-height vehicles around shall be provided prior to the tunnel entrance.

The over-height detection system alarm points shall be based on AASHTO required vertical clearance within the tunnel. The over-height detection system shall locate receiver/transmitter pairs along the roadway such that the paths between each transmitter-receiver pair shall be parallel such that the beams between the pairs shall define a plane parallel to the detection height.

The over-height detection system shall operate in conjunction with other traffic control components. In the event of an interruption of the beams crossing the roadway in the appropriate sequence, the detector controller shall activate a downstream message, and an audible alarm and strobe light shall warn the driver of the over-height vehicle and provide instructions. An alarm shall also be generated at the remote control room.

Means shall also be provided to stop traffic from entering the approaches to the tunnel as described in NFPA 502. Direct approach roads to the tunnel shall be closed following the activation of a fire alarm in the tunnel. These approaches shall be closed in such a manner that responding emergency vehicles are not impeded in transit to the fire site.

capable of negotiating a small radius curve. The TBM radius is a function of the diameter of the TBM as well as its overall configuration.

The limitations listed here serve to create the visual impression of curvature to the driver which will be in line with driver expectations inside the tunnel. Additionally, minimizing chord lengths will assist with stopping sight distance.

2.8—SYSTEMS

The need for tunnel systems shall be based upon the length, location, and alignment of the tunnel. Owners shall undertake studies, including hazard analyses, to determine the appropriate systems required. Not all systems specified herein may be required. When required, systems shall meet the minimum requirements set forth herein.

Systems shall be integrated to be complimentary and be able to be monitored from a remote location(s). A vulnerability study shall be included in the systems integration design to ensure redundancy in critical systems and to avoid failures of multiple systems as a result of the failure of a single system.

Consideration shall be given to the potential of flooding of the tunnel when locating and designing system components. System components shall be designed to be resistant to flooding when it is not possible to locate them outside of areas that could be flooded during an extreme event.

2.8.1—Codes and Standards

The latest edition of the following codes and standards are applicable to the design of tunnel systems and shall be used in the absence of specific design criteria developed by the Owner.

- AMCA—Fans and Systems Applications Handbook
- ANSI/IEEE—ANSI C2 National Electric Code Lighting
- ANSI/IES RP-8—Standard Practice for Roadway Lighting
- ANSI/IES RP-22—Standard Practice for Tunnel Lighting
- ASHRAE Handbook of Fundamentals
- CIE 88:2004—Guide for the Lighting of Road Tunnels and Underpasses
- CIE 193:2010—Emergency Lighting in Road Tunnels
- FHWA—HEC-12, Drainage of Highway Pavements
- ICC—International Fire Code (IFC)
- I.E. Idelchik, Handbook of Hydraulic Resistance
- ITA—Guidelines for Structural Fire Resistance for Road Tunnels
- NFPA 30—Flammable and Combustible Liquids Code

C2.8

It is recommended that the operation and maintenance staff be included in the design, detailing, and integration of the tunnel systems.

Recent events, such as Hurricane Sandy, which occurred in October 2012, should be considered during the design of tunnel systems. Extreme events in coastal areas can cause unanticipated tunnel flooding. Designing resilient, flood resistant systems will result in a quicker recovery from a catastrophic flood event.

- NFPA 37—Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines
- NFPA 70—National Electrical Code
- NFPA 72—National Fire Alarm Code
- NFPA 78—Safety Code for the Protection of Life and Property Against Lightning
- NFPA 780—Standard for Installation of Lightning Protection Systems
- NFPA 92B—Standard for Smoke Management Systems in Malls, Atria, and Large Spaces
- NFPA 502—Standard for Road Tunnels, Bridges, and other Limited Access Highways
- UL 96A—Installation Requirements for Lightning Protection Systems
- UL 1008—Standard for Safety Transfer of Switch Equipment

2.8.2—Supervisory Control and Data Acquisition (SCADA) System C2.8.2

Where such systems are required by NFPA 502, a comprehensive supervisory and control and data acquisition (SCADA) system shall be provided to permit monitoring and controlling of life-safety systems and equipment throughout the facility.

The Engineer shall specify the equipment required to be controlled and monitored by the SCADA system specific to each facility based on design guidelines, standards, codes, and local agencies. The Engineer shall coordinate the system requirements with the Owner or operating authority. At minimum, all equipment required for safe normal and emergency operation of the tunnel fire life-safety systems and equipment should be controlled and monitored by the SCADA system.

The architecture of the SCADA system shall employ a fail-safe redundant backbone (network) topology. The system architecture shall be designed with a redundant 'hot-standby' programmable microprocessor based control system, such as a programmable logic controller (PLC), capable of seamless transfer of data upon failure of one of the processors or network connection. These PLCs shall be connected to distributed input/output (I/O) cabinets and remote input/output (RIOs) through redundant communications links. The RIO cabinets shall be strategically located throughout the facility to interface with life-safety systems and equipment to minimize hardwire cable/wire runs between field devices and the SCADA system.

The SCADA system shall employ a universal remote input/output open network protocol, allowing different network manufactured devices the ability to

communicate with the PLCs and RIO cabinets. Each remote input/output cabinet shall be designed to accommodate the required number of points for the digital input (DI), digital output (DO), analog input (AI), and other data modules as needed to control and monitor connected equipment, with an additional fifty percent (50%) spare for each point type (DI, DO, AI, etc.). The remote I/O cabinet shall be housed in an appropriately rated National Electrical Manufacturer's Association (NEMA) enclosure suitable for the environment to where it will be installed.

The design of life-safety mechanical and electrical systems and equipment shall incorporate provisions for communication, control, monitoring, and indication, to the SCADA system.

The SCADA system shall consist of redundant, reconfiguring communications networks (backbone), servers, and human operator interfaces (HMI) at the head end to facilitate operator interface. The head end communications network shall consist of dual fault tolerant, redundant, reconfiguring fiber optic ring topology with management switches at each node. Servers shall be capable of providing hot standby service as described above.

Operator interfaces shall be provided at a remote control room location and/or locally at the facility as required by the operating agency. Different levels of system access protected by password as defined by the Owner shall be provided. The system shall also be capable of handling and managing data logging and transfer of alarms, alerts, and record keeping for historical purposes, and control and monitoring of equipment related to the life-safety system.

Recordkeeping should be in accordance with the Owner's record retention policy.

2.8.3—Tunnel Ventilation System (TVS)

The TVS shall be designed to maintain environmental conditions within the tunnel and shall also meet the requirements of NFPA 502 for fire and smoke control.

C2.8.3

Most road tunnels require some form of ventilation to mitigate the accumulation of vehicle emissions, and to manage the flow of heat and smoke resulting from a vehicle fire occurring inside the tunnel. Depending on factors such as tunnel length, tunnel geometry, traffic mix, and traffic volumes, certain tunnels may be capable of self-ventilating while others require the assistance of mechanical ventilation systems. Self-ventilating tunnels rely solely on the movement of traffic to provide enough air flow through the tunnel to dilute vehicle emissions and disperse them, typically, through the exit portal. Mechanical ventilation systems in road tunnels are typically designed to assist the movement of air longitudinally through the tunnel; either for the full length of the tunnel or to a location within the tunnel where the vitiated air (or smoke and heat resulting from a fire emergency) can be safely extracted. Mechanical ventilation systems commonly used in road tunnels include transverse and semi-transverse supply and exhaust systems, point extraction (exhaust) systems, jet fan based longitudinal systems, and injection fan

Control and operation of the tunnel ventilation system shall be integrated into a system compatible with the operation plan for the tunnel facility.

The design fire shall be determined based on the types of vehicles and the potential cargos that are anticipated to utilize the tunnel. The following minimum characteristics shall be used to define the design fire:

- Fire heat release rate expressed in MBtu/hr (MW)
- Fire Growth Rate as defined by NFPA 92B
- Fire Smoke Properties:
 - Combustion composition product yield rate
 - Mass specific extinction coefficient
 - Mass fuels rate determination
 - Air fuel ration

NCHRP Synthesis 415 and NFPA 502 shall be referenced for guidance when selecting an appropriate design fire size.

2.8.3.1—Tunnel Ventilation Operational Modes

The various tunnel ventilation modes are defined as:

- *Normal Operations*—Periods of time when vehicular traffic using the tunnel is at average operating speeds (> 30 mph).
- *Congested Operations*—Periods of time when vehicular traffic using the tunnel is impeded from normal traffic flow, but not at a standstill.

(saccardo) based longitudinal systems. Detailed information on these systems can be found in both the *ASHRAE Applications Manual* (Chapter 15) and NFPA 502. The TVS will typically include fans, motors and motor controls, sound attenuators, roadway-to-duct dampers, fan isolation dampers, distribution ducts, turning vanes, air shafts, air plenums, louvers, operating equipment condition monitoring devices, and tunnel environmental monitoring devices.

Every road tunnel is unique in its operational and safety related requirements and determining the capacity and type of tunnel ventilation system to be used is dependent on the variety of influencing factors that are unique to that specific tunnel. NFPA 502 identifies the type of influencing factors that should be considered when determining the overall fire protection and life-safety requirements unique to a specific tunnel facility—including the role and performance requirements of the ventilation system during a fire emergency. Once an appropriate tunnel ventilation system is selected to meet the demands of the potential fire emergency in a specific tunnel, operational variations of that same system can be utilized to meet the non-emergency ventilation requirements such as management of the vehicle emissions under various traffic conditions and equipment outages due to routine maintenance or unexpected failures.

C2.8.3.1

Operational modes of the ventilation system are often pre-programmed as part of the TVS control system to match predetermined traffic and emergency conditions. Activation of the TVS may be automatic, via an environmental monitoring system and/or time-of-day clock and for emergency operation via an automatic fire detection system. The TVS may be also be activated manually by operational staff located either locally at

Average traffic speeds are between 5 mph and 30 mph.

- *Standstill Operations*—Periods of time when vehicular traffic is moving at a speed less than 5 mph or forced to come to stop due to a traffic event outside or inside the tunnel.
- *Emergency Operations*—Period of time from the start of a vehicle fire incident to the time the tunnel is purged of all smoke and the incident scene has been cleared by emergency responders.

the tunnel facility or at a remotely located control center. Manual activation of pre-programmed system modes is based on receipt of alarms or alerts from the traffic monitoring system, environmental monitoring system, incident detection system, fire detection system, or by visual assessment via closed circuit television (CCTV).

2.8.3.2—TVS General Performance Requirements

The TVS shall be designed to provide a safe and tenable environment for motorists in the tunnel during all expected operational conditions.

The TVS shall also be designed to mitigate the effects of smoke and heat during an incident involving a fire to facilitate the safe evacuation of motorists and firefighting operations. The design fire shall be determined based on the types of vehicles expected to use the tunnel and the potential cargo to be transported through the tunnel.

The TVS shall be designed to provide the following minimum functions for the operational modes defined above in Article 2.8.3.1:

1. Dilution and removal of vehicle generated emissions to maintain minimum criteria limits for carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter to reduce haze as defined in Table 2.8.3.2-1. Air quality monitoring and alarms alerting tunnel operators that the in-tunnel air quality is approaching or exceeding these limits shall be an integral part of the TVS operational control concept.
2. Management of the flow of smoke and heat during a vehicle fire event so as to establish and maintain a safe and tenable egress path to allow motorists to evacuate to a safe area if necessary and to facilitate access to the fire site by emergency responders. Reference NFPA 502 for specific minimum requirements.
3. All tunnel ventilation equipment including ductwork and appurtenances exposed to the heated airstream during a fire shall be designed to meet their performance requirements for a minimum of one hour at a temperature of 482 degrees Fahrenheit or according to the calculated additional time requirements as per Article 2.8.3.3.3, whichever is greater.
4. TVS exhaust and supply air shafts shall be protected at grade to prevent the possibility of dangerous substances or foreign objects entering the tunnel. In addition, supply air ventilation intakes shall be located to ensure against the

- recirculation of emissions or smoke from the ventilation exhaust system.
5. When used as a part of the TVS, jet fans shall not be obstructed on the intake or discharge sides by other tunnel fixtures, lighting, or signage. Jet fans shall be provided with sound attenuators that reduce fan noise so that acceptable sound levels are met on the tunnel roadway. Refer to NFPA 502 for guidance on acceptable sound levels.
 6. The TVS shall be designed with sufficient redundancy to ensure its reliable availability. Reference NFPA 502 for minimum requirements.

Table 2.8.3.2-1—Minimum Limits for Carbon Monoxide, Oxides of Nitrogen, and Particulate Matter

Pollutant	Limiting Value
Carbon Monoxide (CO)	120 ppm up to 15 minutes
	65 ppm up to 30 minutes
	45 ppm up to 45 minutes
	35 ppm up to 60 minutes
<i>Oxides of Nitrogen (NO_x)*:</i>	
Nitric Oxide (NO)	25 ppm
Nitrogen Dioxide (NO ₂)	1 ppm
Haze	K = .0001521 / foot**

* The main constituents of NO_x are NO and NO₂

** K is an extinction coefficient which is a measure of the amount a light beam is attenuated

CO limiting values are based on FHWA/EPA guidelines. The NO limiting value is based on TWA established by the National Institute for Occupational Safety and Health (NIOSH). The NO₂ limiting value is based on recommendations made by the World Health Organization and the World Road Association (PIARC). K is an extinction coefficient, which reflects the amount a light beam is attenuated over a given distance.

2.8.3.3—TVS Design Analysis Calculations

The following minimum calculations are required for the design of the TVS.

2.8.3.3.1—Emissions Ventilation Flow Rate

The emissions ventilation flow rate is defined as the amount of airflow required to maintain criteria limits for CO, NO_x, and visibility (haze) generated by vehicles at

various speeds. The emission's ventilation rate shall be determined based upon average projected peak traffic speed and density data. In addition, the average projected traffic mix shall be used in this and other applicable calculations.

The total required emission ventilation rate shall also consider the piston effect (the amount of airflow generated by the movement of vehicles) which shall be based on the vehicle velocities associated with the traffic density data. The United States Environmental Protection Agency's (EPA) emissions prediction software Mobile 6.2 shall be used to prepare the vehicle emissions factors.

Consideration of any adverse wind conditions at the exit portal(s) is also required when determining emission ventilation flow rates and shall be based on typical winds in the geographical area of the tunnel. A 90th percentile of the winds impinging upon the exit portal shall be used for the tunnel ventilation analysis. The prevailing wind direction with respect to the tunnel axis shall be taken into account in calculating the portal design wind.

The determined emission ventilation flow rates from the tunnel shall be used to perform an emissions dispersion analysis to demonstrate that pollutant concentrations at nearest ambient receptors to the tunnel portals or exhaust ventilation structures are in compliance with applicable local, state, and federal air quality regulations.

2.8.3.3.2—Emergency Ventilation Capacity

The amount of airflow required for adequate smoke and heat control during a fire emergency shall be determined using computational fluid dynamics (CFD) modeling. These analyses shall also estimate the smoke movement and gas temperatures within defined regions both upstream and downstream of the fire. Peak temperature at the surface of the tunnel structure in the region of the fire shall also be predicted.

CFD modeling of fire and smoke movement shall use the design fire established for the tunnel. The design fire size used for determining the emergency ventilation requirements for a specific road tunnel shall be selected based on the complete evaluation of all influencing factors specific to the tunnel.

2.8.3.3.3—Egress Calculations

The spacing of the cross-passages shall be verified as adequate for fire life-safety purposes by performance of egress modeling, coupled with the emergency ventilation model. The movement of smoke shall be modeled on a transient basis and shall be compared to the egress time duration. Egress modeling shall be accomplished via computer simulation.

2.8.3.3.4—Fan Sound Attenuation

A noise analysis shall be performed to demonstrate that the TVS operates in compliance with applicable sound criteria at the roadway level and sidewalk level in

the TVS fan room. The noise analysis shall include nearby sensitive receptors to ensure compliance with local noise ordinances.

2.8.3.4—Engineering Design Software

2.8.3.4.1—CFD Flow Modeling Software

CFD flow modeling software shall be used for the fire and ventilation system airflow modeling. The CFD software shall be able to:

- Predict air temperatures at defined regions,
- Consider the effects of duct leakage, and
- Predict the region of smoke and heat control within the tunnel roadway.

2.8.3.4.2—Egress Modeling Software

Egress modeling software shall have a publicly available validation report with technical information and the following capabilities:

- Simulating various types of tunnel occupants based on gender and age variations, differences in body dimensions and mobility, travel speed, and pre-movement time.
- Simulating the tunnel occupant movements as a function of time.
- Accounting for the effect of crowded conditions on tunnel occupant travel speeds.
- Modeling of the tunnel occupant speeds as a function of vertical travel, both up and down.
- Identifying locations and durations of choke points along the egress paths.
- Providing numerical output as a function of time, the cumulative number of tunnel occupants who have passed each exit or have yet to exit.

2.8.4—Drainage System

Tunnel drainage systems shall be designed to collect and discharge water that can accumulate in the tunnel due to seepage of the structure, rainfall overflow from approach roadways, snow melt, tunnel washing, or firefighting activities. Water shall be collected through inlets into pipes and conveyed via gravity to a sump location that also serves as a pump station.

Collected water may be pre-treated on-site prior to discharge or discharged directly into a sanitary system prior to discharge into natural waterways. All discharged water shall meet local standards for quality prior to discharge into natural waterways.

No inlet structure or portion thereof shall be located in the roadway surface of the travel lanes. Flows shall not extend into the travel lanes. All components of inlets shall be designed to carry the same traffic loading as other components of the tunnel.

Cleanouts shall be provided at intervals that facilitate proper functioning of the system, and at all locations that

C2.8.3.4.1

Commercially available software that satisfy these criteria are: FDS (Fire Dynamics Simulator available from NIST), CFX (available from ANSYS), FLUENT (available from ANSYS), SOLVENT (available from Parsons Brinckerhoff), and STAR-CD (available from CD-adapco).

C2.8.3.4.2

Commercially available software that satisfy these criteria are: SIMULEX, STEPS (available from Mott MacDonald Group, Limited), and LEGION EVAC (available from Legion, Limited).

C2.8.4

would be prone to collecting debris that could clog the system.

Tunnel drainage systems shall be designed in accordance with NFPA 502 and capable of capturing and conveying spills of hazardous or flammable liquids with minimum propagation.

Operational protocols such as shutting down discharge pumps in the event of a fuel spill shall be developed to ensure that effluent discharged by pumps meets regulatory requirements.

Owners shall establish the rules for cargo during the planning stage in order to provide guidance to Engineers regarding the requirements for drainage and pump systems

Storm water generated on the immediate approach roadways outside the tunnel portals shall be intercepted to prevent it from entering the tunnel.

The tunnel drainage systems shall be sized to handle the largest anticipated flows.

Operational protocols for discharges from the tunnel drainage systems shall comply with all applicable local and federal environmental regulations.

Miscellaneous drains shall be provided in spaces such as equipment rooms, egress passages, stairwells, etc. and connected to main tunnel drainage system.

For road tunnels in climates where freezing conditions are probable, drainage shall not be permitted to cross over the travel portion of the roadway.

The drainage system components shall be evaluated for the potential of freezing during cold weather and consideration shall be given to protecting the drainage system from freezing.

The pump station shall be located and sized to provide access for maintenance, repair, and replacement of the pumps as well as access for clean out of the sump area. Pumps shall be sized to handle the design flows. Redundant pumps shall be employed. Access to the pump station shall be out of the travel lane whenever possible. If required, access manholes shall be located in the center of the travel lane away from the wheel track area.

The pump station shall be designed with settling basins, weirs, and screens as required for pre-treatment of collected effluent and to prevent any large solids from entering the pumps.

Tunnel drainage systems can be the recipients of a variety of liquids, including water, washing and firefighting chemicals, motor vehicle fuels, and lubricants and liquid cargo of all types.

Tunnel operational practices and restrictions on cargo permitted to be transported through the tunnel can assist in limiting the types of liquids required to be conveyed and handled by the tunnel drainage system.

The purpose of intercepting storm water at the tunnel portals is to avoid the need for a significantly larger pump station and equipment to handle typical storm flow conditions.

Wash water loads typically vary from 150 to 500 gallons per minute. Firefighting loads are determined based on the fire suppression system design flow. Tunnel seepage requirements are determined based on the preference of the Owner. Typical values are generally less than one gallon/minute/1,000 feet of tunnel.

Other areas requiring drainage considerations include ventilation ducts and safety or maintenance walks. It is also recommended that any electrical raceways, pull-boxes, and hand holes be provided with drainage systems that connect to the tunnel drainage system. This will allow conduits that may fill with water to drain.

Locations of reverse curves where super elevation changes direction are locations where drainage can cross over the roadway

The basic components of a roadway tunnel pump station are pumps, discharge piping and operational controls, water level alarms, hydrocarbon detection devices, and ventilation.

2.8.5—Lighting

The lighting design shall comply with the latest applicable manuals listed in Article 2.8.1.

The tunnel lighting shall be designed to provide adequate daytime illumination in the entrance portion of the tunnels, so that motorists can drive a vehicle safely and efficiently at the posted speed conditions, as well as supporting the eye adaptation of the motorist to lower lighting levels in the interior of the tunnel.

2.8.5.1—Tunnel Lighting System

2.8.5.1.1—Design Approach

The design methodology of the tunnel lighting system shall be based on ANSI/IES RP-22. Tables 2 & 3 of ANSI/IES RP-22 may be used for preliminary design, but the equivalent veiling luminance (L_{seq}) method shall be used for final design.

Design of tunnel lighting shall consider the following four zones: approach, threshold, transition, and interior.

The combined length of the threshold and transition zones shall follow the eye adaptation curve defined in ANSI/IES RP-22.

The interior zone immediately follows the combined lengths of the threshold and transition zones. The daytime interior luminance level shall be determined based on the traffic volume as per Table 7 in ANSI/IES RP-22.

The surface reflectances for the tunnel shall be considered in the design of the tunnel. Consideration shall be given for higher reflectance surfaces to benefit from interreflected light within the tunnel. The design shall also consider the maintenance procedures to be used for cleaning these surfaces and how that will affect the maintained lighting values in the tunnel.

The nighttime luminance level shall be uniform through the entire length of the tunnel and provide an

C2.8.5

Tunnel lighting consists of lighting for the tunnel approach and roadway, emergency exit pathways, and ancillary spaces within the tunnel. This article establishes the basic design requirements for the tunnel roadway lighting system.

C2.8.5.1.1

The objective is to utilize the most beneficial luminance level to ensure driver visibility while controlling initial cost.

An equivalent veiling luminance (L_{seq}) analysis determines the adaptation of the eye of an approaching motorist for that specific day/time/condition. After determining the adaptation of the driver, formulas can then be applied to determine how much lighting is needed inside the tunnel in order to see a hazard on the road from outside the tunnel at a safe sight stopping distance (SSSD). Once inside the tunnel, transition zones are used to reduce the lighting levels at a rate which maintains the vision of the driver.

ANSI/IES RP-22 divides the tunnel into separate zones to accommodate the proper adaptation of the human eye. These zones are called 'approach,' 'threshold,' 'transition,' and 'interior.' The length of each zone and the lighting requirements for each zone correlate to the curve of eye adaptation. This curve relates speed to visibility by transforming the rate of eye adaptation to SSSD established by AASHTO. The current standards suggest that one SSSD for the threshold, followed by a 10-second transition will provide enough time for a driver to adapt to the tunnel's interior environment.

Lighting design for tunnels is luminance based design for the roadway. Typical pavements used in the US include R1 which is a concrete pavement and R3 which is asphalt. Pavement types are defined in ANSI/IES RP-8.

Other criteria are given for the walls of the tunnel, and conversions are included in RP-22 in order to use illuminance levels for the wall surfaces.

average luminance level of 2.5 candelas per square meter (cd/m^2).

The interior zone illumination levels shall be extended to the exit portal. An exception to this would be bi-directional tunnels or tunnels that may be used as bi-directional under certain operating conditions. For these cases, a threshold lighting analysis shall be required.

In order to allow for visual accommodation approaching and exiting the tunnel, the entrance approach and exit approach lighting shall be no less than one-third of the nighttime tunnel luminance in order to maintain good visibility.

2.8.5.1.2—Design Parameters

The design parameters that influence the selection of the lighting design are: *LLF*, luminaire efficiency and distribution, reflectance of the interior surfaces, and tunnel geometry. *LLF* is calculated as follows:

$$LLF = (LAT) \times (VF) \times (RSSD) \times BO \times (LLD) \times (LDD) \quad (2.7.5.1.2-1)$$

where:

LAT = Luminaire ambient temperature factor

VF = Voltage factor

RSSD = Room surface dirt depreciation factor

BO = Burn out factor

LLD = Lamp lumen depreciation factor

LDD = Luminaire dirt depreciation factor

Determination of the proper dirt depreciation factor should be through discussions with maintenance personnel and expected environmental conditions of dirt, road spray, and vehicle exhaust.

2.8.5.1.3—Lighting Control System

The tunnel lighting control system shall be designed to operate automatically and maintain a predetermined ratio of outdoor luminance to threshold and transition zone luminance for each roadway, under all weather conditions, during daytime operating hours. The system shall prohibit response to sudden and short duration (less than 15 minutes) light level changes and shall respond only to steady and long duration (more than 15 minutes) changes.

The controller shall also consider the ability to monitor multiple luminance sensors located throughout the tunnel, to monitor the maintained luminance level. When any of the luminance meters sense that the lighting level is less than a specified set point, the system shall provide an alert identifying the need for maintenance to the lighting fixtures.

The lighting control system may be integrated into the SCADA system.

There is general agreement by authorities that the eye's natural ability to quickly adjust to an increasing level of illumination precludes the need for providing a higher light level at the exit portal.

C2.8.5.1.2

Light loss factors are adjustments that are made in order to adjust the lighting calculations to anticipated field conditions. This overall adjustment is dependent on a series of recoverable and non-recoverable factors which will affect the lighting system's operation from the time the system is first turned on, through the life of the system. Refer to ANSI/IES RP-22 for additional information and guidance in determining appropriate values for Equation 2.7.5.1.2-1.

The single largest light loss factor in tunnels is dirt depreciation. Depending on the operating environment and cleaning cycles used, dirt can reduce the output of the luminaires by over 50 percent.

C2.8.5.1.3

A luminance sensor, lighting contactors, and a controller cabinet are the necessary components of a lighting control system. The sensor sends an analog signal to the controller and the corresponding output level is switched on or off using lighting contactors, depending on the frequency received.

The use of lighting controls can greatly improve the ability of the tunnel lighting system to adapt to changing daylight conditions so that when approaching and entering the tunnel, it is easier to ascertain conditions directly beyond the tunnel entrance. Illuminating a tunnel roadway to its highest level of lighting is only necessary during bright and sunny days. Otherwise, considerations should be incorporated into the design to save energy whenever possible. A typical lighting control scheme is depicted in the Table C2.8.5.1.3-1.

Table C2.8.5.1.3-1—Typical Lighting Control Scheme

Control Level	Illumination Level as a Percent of Maximum	Sensor Setting – cd/m ²	
		ON Increasing Light	OFF Decreasing Light
1	4	0–50	35–0
2	10	50–200	180–35
3	35	200–800	700–180
4	60	800–4,000	3,800–700
5	100	>4,000	<3,800

2.8.5.1.4—Tunnel Lighting Fixture Circuitry

Fixtures on opposite sides of the roadway shall be supplied by separate panelboards. These separate panel boards, in turn, shall be connected to switchgear busses normally energized from alternate electrical services. Luminaires shall be circuited that a single circuit failure would not extinguish a large percentage of the normal lighting within the tunnel. To prevent the tunnel from being cast suddenly into complete darkness by simultaneous loss of power from all utility power sources, emergency lighting shall be provided as required by NFPA 502.

2.8.5.1.5—Tunnel Lighting Fixtures

Luminaires shall provide the necessary luminance/control while physically staying outside the dynamic traffic envelope. All luminaires within the tunnel shall be watertight and corrosion resistant to protect their interiors from periodic high-pressure wash downs of the tunnel walls and ceiling. All luminaires within the tunnel areas shall be rated for the type of cleaning expected to be used by maintenance personnel. All of the materials used for the lighting fixture construction and wiring within the tunnel shall meet the requirements of NFPA 502. Metallic components of lighting fixtures shall be compatible with the metallic components of supporting hardware to avoid the corrosion problems associated with dissimilar metals in contact with each other.

C2.8.5.1.5

A tunnel environment requires a high level of corrosion resistance and dust and dirt tolerance. Fixtures and the electrical distribution system are exposed to salt and certain levels of sulfuric acid created from diesel vehicle exhaust. Components also have to be used which tolerate emergency conditions such as fires and if exposed to a fire condition will not cause a hazard within the tunnel like high smoke generation or toxic gases.

2.8.5.2—Tunnel Cross Passages, Egress Stairwells, and Ancillary Spaces

Interiors of cross passages and stairwells shall be designed for an average illuminance of 10 footcandles (100 lux). Circuiting for cross passages and egress stairwells shall be designed in accordance with the requirements of the National Electric Code. Electrical equipment rooms shall be designed for an average illuminance of 30 footcandles (fc). Pump stations, battery rooms, and storage rooms shall be designed for an average illuminance of 20 fc.

Exits within the tunnel shall be clearly identified by dedicated emergency exit lighting that will help vehicle

occupants find the exit when necessary during an emergency. This supplemental lighting provided at the exits shall light the door and surrounding surfaces to a much higher level than the interior of the tunnel, providing the necessary demarcation. This lighting is in addition to the exit markings, strobe lights, directional signs, and other indicators.

In order to make the tunnel exits adequately visible, and to familiarize the driver with their position and geometry, the maintained average vertical illuminance at all times on the door and on an area of tunnel wall extending six feet beyond the projected door frame of an emergency exit or cross passage, or outlining the actual opening in the tunnel wall, shall not be less than four times the adjacent wall illuminance or 10 fc. The overall uniformity (average/minimum) of illuminance on this area shall not be less than 2.0. The light sources used for this lighting shall have a color rendering index of $Ra \geq 60$.

Emergency lighting for these areas shall not be less than one fc, shall utilize a selected number of lighting fixtures provided as part of the general illumination, and shall be connected to a uninterruptable power supply (UPS) system, generator, or other emergency power source capable of maintaining the lighting levels for a minimum of 60 minutes.

Exit sign lighting fixtures shall be provided to illuminate the designated egress passageways, including the entrance to stairways. Exit sign lighting fixtures shall be wet location, wall, or bracket mounted, at a mounting height visible to all occupants within the occupied spaces. All exit sign lighting fixtures shall be connected to the emergency power source.

Additional information regarding signing for tunnel egress can be found in NCHRP 20-59(47) *Emergency Exit Signs and Marking Systems for Highway Tunnels*.

2.8.5.3—Tunnel Fixed Message Sign Lighting

C2.8.5.3

All ceiling mounted, non-internally illuminated signs located in tunnels shall be externally illuminated using the luminance or illuminance methods in accordance with the following criteria:

Luminance—96 candelas per square meter minimum

Illuminance—40 lms/ft² (400 lux) minimum assuming 65 percent maintained reflectance.

The maximum to minimum uniformity ratio on the sign face shall not exceed 4 to 1. The maximum illuminance gradient produced on the sign face shall be 2 to 1.

Fixtures shall be located so that they do not interfere with sign visibility for drivers of any type of vehicle or impact driver visibility for oncoming traffic in two-way tunnels.

Fixtures used to illuminate fixed message signs shall be connected to the tunnel lighting emergency power source.

The external illumination of tunnel fixed message signs may be provided by light fixtures dedicated to this purpose or illuminated by the general tunnel lighting if the lighting criteria is met by the general tunnel lighting system.

2.8.6—Electrical Systems

2.8.6.1—General

Electrical systems shall be designed to provide functionality, durability, ease of maintenance, and safety in accordance with the National Electrical Code and National Electrical Safety Code. The electrical installation shall also comply with local building and electrical codes, as well as tunnel life-safety design guidelines. The electrical requirements of other systems, including mechanical, traffic control, fire and surveillance, and SCADA systems shall be incorporated into the overall design of the tunnel normal and emergency electrical systems. Close coordination with all other disciplines shall be maintained throughout the design process to confirm that the power needs and redundancy of power supply for each system are provided.

2.8.6.2—Primary Distribution

The electrical system shall perform as a fully redundant system utilizing specific switch-over schemes to minimize the impact of a power interruption. Each end of the tunnel shall be provided with a minimum of one independent electrical service feeder from the local utility. If the tunnel is being fed from only one side, then two independent utility service feeders or one feeder with generator backup shall be provided. Independent feeders are defined as those originating from separate utility substations or buses and meeting reliability requirements of National Electrical Code Article 700. The combination of these feeders shall provide primary distribution throughout the normal operation of the entire tunnel facility. Each incoming service feeder shall have the capability of supplying the entire power requirements for the facility, thus providing the redundancy required to maintain tunnel operations during outages, maintenance, or repairs.

The primary distribution system shall be extended from the point of service to the primary switchgear for each service. The primary distribution system shall be designed such that the primary switchgear can be powered from either of two separate utility sources, or single service and backup generator. Necessary cables, transformers, switches, circuit breakers, etc., of each supply shall be separated from each other to the maximum practicable extent.

2.8.6.3—Primary Switchgear

The switchgear assembly and all components shall be designed in accordance with the latest applicable standards of ANSI, NEMA, and the Institute of Electrical and Electronic Engineers (IEEE). The switchgear shall comply with the engineering and operating requirements

of the utility supplying the power. The switchgear assembly shall have sufficient short circuit and impulse withstand capability to operate safely, and properly coordinate with the utility company service being provided to protect the electrical equipment being provided. Main, tie, and feeder circuit breakers shall be fully rated for continuous service and be sized for the connected loads in accordance with the National Electrical Code.

Provisions shall be included in the design to accommodate the required SCADA functions to permit operation of selected breakers, and remote monitoring and/or alarming of electrical system conditions and breaker positions from a central location

The switchgear shall be installed within an area of the ancillary buildings at the tunnel portals or other suitable locations, or near the utility company service entrance. Spaces containing this equipment shall be positively pressurized and provided with sufficient filtered air, free of moisture, to maintain the ambient temperature below a maximum 104°F.

Primary switching equipment shall be metal-enclosed or metal-clad.

Power transformers, when required for services above 600 volts, shall be UL listed, and step down of the medium voltage service to the required utilization level voltage. Transformers shall be located within interior rooms, where possible, with sufficient filtered or dust-free air, free of moisture, to maintain a maximum ambient temperature of 104°F. Wherever feasible, transformers shall be joined to primary and secondary switchgear in double-ended unit substation configurations.

2.8.6.4—Secondary Distribution Systems

C2.8.6.4

This article specifies minimum requirements for secondary distribution systems, i.e., electrical distribution systems operating at a voltage level below the primary distribution system medium voltage at utilization voltage levels.

These systems include utilization voltage switchgear, motor control centers, distribution, lighting and power panelboards, motor controls, outlets and receptacles, raceway systems, and wiring.

2.8.6.4.1—Low Voltage Switchgear/Switchboard

Low voltage switchgear/switchboards shall consist of circuit breakers positioned in metal-enclosed or metal-clad, free-standing enclosures. In general, the switchgear/switchboard shall be arranged for attachment to a transformer enclosure as a component of a unit substation when possible. Switchgear/switchboard sections for low voltage service applications shall include main circuit breakers capable of interfacing with the local utility company.

The switchgear/switchboards shall comply with the latest applicable standards of ANSI, NEMA, and IEEE and shall include the capability to interface with the SCADA system to provide remote operation of selected breakers, and remote monitoring and alarming of electrical systems conditions and breaker status.

Main and tie circuit breakers in double-ended substation configurations shall be electrically interlocked to prevent both transformers from being paralleled. Additionally, electrical interlocks shall be provided as required to fulfill operational conditions and coordination with the utility company. In addition, mechanical interlocks shall be provided for personnel safety under all conditions of operation and maintenance. Indoor switchgear/switchboards shall be installed within an area of the ancillary building, or other suitable space, set aside for electrical equipment and accessible to authorized personnel only. Equipment may also be located outside in suitably NEMA rated environmental enclosures.

2.8.6.4.2—Panelboards

Panelboards shall be the bolted circuit breaker type.

2.8.6.4.3—Motor Controllers and Control Devices

Solid state, adjustable speed controllers, or reduced voltage starters shall be provided for poly-phase motors and shall be sized to start the equipment motors in accordance with NEMA MG1. Life-safety control features shall be incorporated into starters or controllers for emergency tunnel ventilation fan motors.

Automatic control of emergency tunnel ventilation fan motors shall be provided using programmable microprocessor based control systems for remote control and monitoring. Local control shall be provided from the associated starters or controllers.

2.8.6.4.4—Dry-Type Distribution Transformers (600 Volts and Below)

Transformers shall be Underwriters Laboratory (UL) listed. Transformers shall meet NEMA TP-1 standards for energy efficiency.

2.8.6.4.5—Power and Convenience Outlets

Ancillary spaces inside the tunnel such as pump rooms, valve rooms, electrical rooms, cross passages, and sprinkler rooms shall be provided with a sufficient number of convenience type receptacles spaced around the perimeter of the interior walls or otherwise located in such a manner as to meet the power requirements of portable equipment.

2.8.6.4.6—Conductors and Cables

All conductors and cables shall be copper except for fiber-optic type cables. Conductors No. 9 American wire gauge (AWG) and smaller may be solid; No. 8 AWG and larger shall be stranded. Minimum size conductors shall be No. 10 AWG for feeders and branch circuits, except those branch circuits connecting convenience receptacles and light switches where No. 12 AWG minimum is acceptable; No. 14 AWG minimum for control, signal, and alarm circuits, and No. 16 AWG minimum for fixture wire.

All wire and cable shall be NFPA 70, thermosetting; heat, moisture, and flame retardant; and compliant with the specific requirements of NFPA 502 for construction and smoke emissions under combustion.

2.8.6.4.7—Standby Power Systems

Standby or emergency power from engine generators, or other type of prime mover or source shall be provided for systems identified by the Owner and/or NFPA 502. The provision of UPS for selected loads that would be adversely affected by even a momentary switching outage is covered in Article 2.8.6.4.8.

The standby or emergency power system shall consist of generator(s) or other type of prime mover or source, switchboards, transfer switches, fuel supply and storage as required, accessories, and wiring required to provide standby power to the systems identified.

2.8.6.4.7.1—Generator Units

Generators shall be designed to perform under the environmental conditions to which they will be subjected.

The required operating and capacity characteristics of the generator, based on a risk analysis that includes the consequences of failure of the generator, shall be as determined by the Owner.

Storage tanks shall conform to all local regulations. The system shall conform to NFPA 30, NFPA 37, and NFPA 110. Fuel type shall be such that exhaust emissions comply with environmental laws. The cooling system shall be designed to discharge heat outside of the building or enclosure housing the generator. Generators shall be equipped with appropriate silencers. Exhaust shall be released outside the building or enclosure housing the generator.

Automatic transfer switches shall conform to UL 1008.

2.8.6.4.7.2—Generator Switchboard

The switchboard shall be an indoor or outdoor type, metal-enclosed, self-supporting structure. The switchboard shall be compartmentalized in design, with individually mounted devices in the distribution sections. The switchboard shall comply with all applicable provision of UL 891 and NEMA PB-2.

2.8.6.4.8—Uninterruptible Power Supply (UPS)

UPS units shall supply uninterruptible power supplies for selected loads. The loads designated to be supplied by the UPS shall be determined by the Owner and/or as required by NFPA 502. Battery protection time shall be determined by the Owner.

Electrical power service loads which are provided with UPS shall be backed-up by a standby power system as described in Article 2.8.6.4.7. The UPS systems shall be designed to operate “on line” such that when normal power fails to the unit, the batteries will provide power for a designated period through the inverter output. If a

C2.8.6.4.8

Typical loads that are connected to UPS are:

- Traffic surveillance and control system (TSCS) equipment.
- Communications, SCADA, and fire detection and alarm systems.
- Selected tunnel, utility room, cross passage, and egress stair lighting.
- Illuminated emergency exit signs.

UPS malfunctions, a static switch shall automatically connect the load to a “reserve” supply while simultaneously opening the inverter-output circuit breaker. A maintenance by-pass shall also be provided to manually transfer the load to the normal supply for routine service or maintenance of the UPS.

The UPS equipment enclosure shall be suitable for the environment in which it is to be installed, recognizing that heat buildup and moisture act to diminish the reliability of a UPS unit.

UPS units, whenever feasible, shall be located in spaces which are relatively dry and adequately ventilated with clean air. This criterion shall be weighed against the desirability of locating the UPS unit as close as possible to the load served, so as to reduce to a minimum the length and exposure of direct current (DC) wiring and the UPS output wiring. A provision shall be made for the required monitoring, control, and alarm functions to the SCADA system.

2.8.6.5—Grounding, Bonding, and Lightning Protection

Electrical equipment shall be grounded to provide safety for personnel and to provide fast, reliable relaying response in accordance with the requirements of the National Electrical Code. Grounding shall be separate but coordinated with corrosion control requirements.

2.8.6.5.1—Systems Grounding

The following grounding requirements shall apply:

1. Three-phase, three-wire, 60 Hertz systems supplied from transformers shall be solidly grounded at the transformer enclosure as per NFPA 70.
2. Three-phase, four-wire systems shall be solidly grounded at their source (transformer secondary, standby generator neutral, or UPS neutral) per NFPA 70.

A connection of the system to earth shall be provided at each substation or switchgear/switchboard section. The connection to earth shall have a sufficiently low resistance to permit prompt operation of the circuit protective devices in the event of a ground fault, and to provide the required safety from shock to personnel who may be in the vicinity of equipment frames, enclosures, conductors, or the electrodes themselves. The connection to earth shall consist of a number of individual driven ground rods connected to a grid or mat system. The grid or mat system shall consist of a number of buried conductors forming a network of squares or rectangles. Buried conductors shall be interconnected at each crossover point by an exothermic welding process. The ground grid or mat shall be connected to ground rods as required. Grids or mats shall be buried in filled trenches or laid on earth and overlaid with at least 18 inches of

backfill. Grid or mat locations shall be coordinated with utilities and sewer installations to avoid any direct electrical connection to these systems. The connections to earth shall be designed in such a way that the system resistance measured at the main ground bus in the switchgear room will not exceed two ohms. Grounding systems other than grids or mats that comply with the National Electrical Code may be provided as the location and design require. Medium voltage switchgear shall be grounded in accordance with IEEE 80 for step and touch potential.

Inside spaces with electrical distribution equipment or motors, a minimum 36 in. long by 2 in. wide copper ground bus shall be installed. These ground buses shall be connected to the main ground grid using copper cables.

2.8.6.5.2—Equipment Grounding

The equipment grounding system shall be interconnected by means of equipment ground conductors to a ground bus in each distribution equipment enclosure such as switchgear, panelboard, motor control center, load center, and ground bus. Every feeder, circuit, and branch circuit shall contain an equipment ground conductor within the same raceway with the phase and neutral conductors. The ground cable shall be connected to the ground bus located in the distribution equipment. The equipment ground conductor shall be copper, sized to comply with the National Electrical Code. The equipment ground conductor shall be continuous throughout the system, connecting all non-current carrying enclosures, tunnel structural grounds, and equipment and machinery grounds.

Medium voltage cable shields shall be grounded at each splice and cable termination.

The non-current carrying parts of electrical equipment, devices, panelboards, and metallic raceways shall be bonded to the local ground bus.

2.8.6.5.3—Grounding for Personnel Safety

Grounding for personnel safety shall be provided to minimize shock hazards as follows:

- In pumping stations, all exposed metallic structures, ductwork, and piping shall be bonded to the local ground bus with a ground conductor.
- All exposed structural metalwork, such as doors, handrails within reach of electrical equipment (five ft±), and all stairways, shall be bonded to the nearest local ground bus.
- In all manholes, handholes, and pull boxes, the ground conductors shall be connected to all exposed, metal surfaces including cable racks, frames and covers, ladders, and cable shields (for medium voltage systems). In addition, in manholes and handholes, a ground conductor shall be further connected to the ground mat installed at the base of each manhole or handhole or to a local ground electrode for the

express purpose of providing for personnel safety. Where the ground grid, mat, or local grounding electrode cannot be installed, a bare grounding conducting coil looping around the exterior of the manhole or handhole multiple times may be used as the local ground.

2.8.6.5.4—Grounding Materials

Driven ground rods shall be sectional steel rods, each 3/4 in. by 10 ft long minimum, coupled and driven to the required total depth. The rods shall be manufactured from type 316 or 316L stainless steel.

Buried grounding conductors used to form the ground grid, mat, or used to connect the individual ground rods, shall be stranded bare copper cable with a minimum size of #4/0 AWG. Equipment and systems grounding conductors shall be stranded copper covered with green insulation and be of minimum size in accordance with NFPA 70.

Ground bus shall be copper. Wall mounted ground bus shall be mounted on insulators above the floor.

Ground connections of cable to building steel, and cable-to-cable shall be exothermically welded. Exothermically welded connections shall be coated with coal tar epoxy or equivalent waterproofing coating to prevent corrosion of the connection.

Connections of ground cable to equipment ground lugs shall utilize two-bolt lugs.

2.8.6.5.5—Lightning Protection

Lightning protection systems and equipment shall be installed, where required, to provide protection of persons, equipment, and facilities against the hazards posed by lightning. The lightning protection system shall comply with the requirements of an Underwriters' Laboratory (UL) "Master Label System" as per UL 96A and NFPA 780.

2.8.7—Tunnel Architectural Systems

2.8.7.1—General

C2.8.7.1

The tunnel architectural systems shall be designed to provide functionality, durability, ease of maintenance, driver safety and orientation, and a uniform and pleasing aesthetic quality, while conforming to applicable codes and standards.

The texture, color, and patterns of ceilings, walls, and walkways, and of related elements, shall create a safe interior driving environment for the motorist that assists driver orientation. Only materials that are fire resistant, and generate limited smoke and do not produce toxic fumes under fire conditions shall be used. Interior finishes in tunnels shall be ASTM E84 Class A (flame spread, 25 or less; smoke developed, 100 or less).

Finish materials shall be easy and economical to maintain. Surfaces shall be easy to clean with standard

Architectural finishes provide lane definition, assist in legibility of signage through sign placement, and support rapid identification of emergency exits.