FTA Report No. 0231

FTA
RESEARCH
FEDERAL TRANSIT ADMINISTRATION

Research Report and Findings: Specifications and Guidelines for Rail Tunnel Design, Construction, Maintenance, and Rehabilitation

PREPARED BY

Anna Rakoczy, Stephen Wilk, MaryClara Jones
Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads

U.S. Department of Transportation
Federal Transit Administration

OCTOBER
2022

COVER PHOTO

Courtesy of Adobe Stock, #93577898

DISCLAIMER

Research Report and Findings: Specifications and Guidelines for Rail Tunnel Design, Construction, Maintenance, and Rehabilitation

OCTOBER 2022

FTA Report No. 0231

PREPARED BY

Anna Rakoczy
Stephen Wilk
MaryClara Jones
Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads
55500 DOT Road
Pueblo, Colorado 81001

SPONSORED BY

Federal Transit Administration
Office of Research, Demonstration and Innovation
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

AVAILABLE ONLINE

https://www.transit.dot.gov/about/research-innovation

Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE October 2022	2. REPORT TYPE Final	3. DATES COVERED 2017–2018

4. TITLE AND SUBTITLE
Research Report and Findings: Specifications and Guidelines for Rail Tunnel Design, Construction, Maintenance, and Rehabilitation

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Anna Rakoczy, Stephen Wilk, MaryClara Jones

5d. PROGRAM NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSE(ES)
Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads
55500 DOT Road
Pueblo, CO 81001

8. PERFORMING ORGANIZATION REPORT NUMBER

FTA Report No. 0231

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Transit Administration
Office of Research, Demonstration and Innovation
1200 New Jersey Avenue, SE, Washington, DC 20590

10. SPONSOR/MONITOR'S ACRONYM(S)
FTA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12 . DISTRIBUTION/AVAILABILITY STATEMENT
Available from: National Technical Information Service (NTIS), Springfield, VA 22161; (703) 605-6000, Fax (703) 605-6900, email [orders@ntis.gov]; Distribution Code TRI-30

13. SUPPLEMENTARY NOTES [www.transit.dot.gov/research-innovation/fta-reports-and-publications] [https://www.transit.dot.gov/about/research-innovation] [https://doi.org/10.21949/1527644] Suggested citation: Federal Transit Administration. Research Report and Findings: Specifications and Guidelines for Rail Tunnel Design, Construction, Maintenance, and Rehabilitation. Washington, D.C.: United States Department of Transportation, 2022. https://doi.org/10.21949/1527644.

14. ABSTRACT

Industry needs related to rail tunnel design, construction, maintenance, and rehabilitation were identified by reviewing past tunnel incidents and discussions with multiple transit agencies. Compilation of past tunnel incidents includes available reports published by the National Transportation Safety Board (NTSB) and other U.S. and European agencies. The tunnel structural design section covers geotechnical exploration/investigation, geometrical requirements and clearances, load and load combination, structural material and design considerations, waterproofing, and seismic design. Selection of tunnel type is based on geometrical configurations, ground conditions, type of crossing, and environmental requirements, and ground/structure interaction is important in the design process. Good knowledge of the expected geological conditions is essential. Tunnel structural components should satisfy many limit states: (1) service limit state as restriction on stress, deformation, and crack width under normal service conditions; (2) fatigue and fracture limit state as restriction on stress range; (3) strength limit state to ensure strength and stability; and (4) extreme event limit state to ensure the structural survival of a tunnel during a major earthquake, flood, tsunami, collision, blast, or fire. Special consideration is given to waterproofing systems and seismic design.

15. SUBJECT TERMS
Rail transit tunnel, tunnel structures, design, rehabilitation, safety

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	Unlimited	132	19b. TELEPHONE NUMBER

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abstract

Industry needs related to rail tunnel design, construction, maintenance, and rehabilitation were identified by reviewing past tunnel incidents and discussions with multiple transit agencies. Compilation of past tunnel incidents includes available reports published by the National Transportation Safety Board (NTSB) and other U.S. and European agencies. The tunnel structural design section covers geotechnical exploration/investigation, geometrical requirements and clearances, load and load combination, structural material and design considerations, waterproofing, and seismic design. Selection of tunnel type is based on geometrical configurations, ground conditions, type of crossing, and environmental requirements, and ground/structure interaction is important in the design process. Good knowledge of the expected geological conditions is essential. Tunnel structural components should satisfy many limit states: (1) service limit state as restriction on stress, deformation, and crack width under normal service conditions; (2) fatigue and fracture limit state as restriction on stress range; (3) strength limit state to ensure strength and stability; and (4) extreme event limit state to ensure the structural survival of a tunnel during a major earthquake, flood, tsunami, collision, blast, or fire. Special consideration is given to waterproofing systems and seismic design.

This report was prepared for the Center for Urban Transportation Research (CUTR) by Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads (AAR), Pueblo, Colorado. It is based on studies conducted by TTCI with the direct participation of CUTR to criteria approved by them. The contents of this report imply no endorsements whatsoever by TTCI of products, services, or procedures, nor are they intended to suggest the applicability of the test results under circumstances other than those described in this report. The results and findings contained in this report are the sole property of CUTR. They may not be released by anyone to any party other than CUTR without the written permission of CUTR. TTCI is not a source of information concerning these tests, nor is it a source of copies of this report. TTCI makes no representations or warranties, either express or implied, with respect to this report or its contents. TTCI assumes no liability to anyone for special, collateral, exemplary, indirect, incidental, consequential, or any other kind of damages resulting from the use or application of this report or its contents.

Executive Summary

Transportation Technology Center, Inc. (TTCI), with support from the Center for Urban Transportation Research (CUTR) at the University of South Florida, was tasked by the Federal Transit Administration (FTA) to research areas of transit safety risk, identify existing specifications and guidelines for rail transit tunnel design, construction, maintenance, and rehabilitation, and perform a gap analysis to establish the need for additional standards, guidance, or recommended practices to support and further the safe operation of the nation's public transportation industry.

The project objectives include: (1) performing an extensive literature review to summarize and compare current specifications, guidelines, and standards for rail transit and road tunnels in the United States (U.S.) and other countries, (2) performing a gap analysis to determine deficiencies in the current standards, and (3) providing recommended voluntary standards and guidance documents that can be utilized in the industry to mitigate areas of risk associated with rail tunnels. The Task 1 report covered the first two objectives and this final report covers all three objectives.

Industry needs were identified by reviewing past tunnel incidents and discussions with multiple transit agencies. The compilation of past tunnel incidents includes available reports published by the National Transportation Safety Board (NTSB) and other U.S. and European agencies. These reports generally involve rare but high-risk events such as fires and flooding and emphasize public safety. A summary of needs obtained through discussions with U.S. transit agencies emphasizes the current practices in day-to-day operations. The industry needs findings include the need for working fire detection, ventilation, and emergency egress along with coordinated emergency response plans that can be used by trained personnel. The findings from the transit agency discussions include the need for more comprehensive guidelines for daily inspections and potential technologies that could be utilized.

An additional literature search was conducted to compile a list of existing design, construction, inspection, and maintenance standards and guidelines for railway and roadway tunnels. A comparison of standards was also completed. This review shows that multiple applicable standards and guidelines exist for rail transit agencies, but they do not always address the rail tunnels directly. Both European (railway) and U.S. (roadway) standards for emergency egress and fire exits could potentially serve as a baseline for future supporting system standards. The design, construction, inspection, and maintenance manuals are typically standards or guidelines of best practices.

The tunnel structural design section covers geotechnical exploration/investigation, geometrical requirements and clearances, load and load combination, structural material and design considerations, waterproofing, and seismic design. The selection of tunnel type is based on the geometrical configurations, ground conditions, type of crossing, and environmental requirements. The ground/structure interaction is important in the design process. Good knowledge of the expected geological conditions is essential. The report presents many geological investigation methods and references to reports and supplementary documents. Tunnel structural components should satisfy many limit states: (1) the service limit state as restriction on stress, deformation, and crack width under normal service conditions; (2) the fatigue and fracture limit state as restriction on stress range; (3) the strength limit state to ensure strength and stability; and (4) the extreme event limit state to ensure the structural survival of a tunnel during a major earthquake, flood, tsunami, collision, blast, or fire. Special consideration in the report is given to waterproofing systems and seismic design.

The tunnel construction section covers tunnel shape, excavation methods, initial support systems, tunnel lining, and ventilation during the construction. Many excavation methods are available for railroad tunnel construction, and the type typically depends on the depth, subsurface condition, surrounding structures, and cost. Several construction methods are described in the report: cut-and-cover; mined tunneling; Tunnel Boring Machine (TBM), Sequential Excavation Method (SEM), also known as New Austrian Tunneling Method (NATM); immersed tunneling; and jacked box tunneling.

The supporting system section covers two primary documents regarding the standards and regulations related to fire and risk assessment in tunnels. The first document is the road tunnel standards published by the National Fire Protection Association (NFPA).[1] The second document is the rail transit tunnel regulations published by the European Union.[2] The codes have different scopes and focus on different topics. Specifically, the NFPA code focuses on fire prevention or mitigation and the European Union Safety in Railway Tunnels (SRT) – Technical Specification for Interoperability TSI (SRT TSI) codes focus on passenger evacuation.

The tunnel security and risk assessment section presents various standards, guidelines, and regulations regarding tunnel security and risk along with tunnel support systems. These two areas are combined because tunnel supporting systems are typically required for security and risk reasons.

---

[1] NFPA (National Fire Protection Association), *NFPA 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways*, 2010.

[2] EU (European Union), Commission Regulation (EU) No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to “safety in railway tunnels” of the rail system of the European Union. Brussels, Belgium, 2014.

The next section covers data collection on the rail transit tunnels in service in the U.S. and practices used by U.S. transit agencies. The results show that at least 17 transit agencies have tunnels and utilize a wide range of inspection practices and manuals for design, inspection, and maintenance. The purpose of the data collection was to (1) determine which standards are being used and (2) summarize general tunnel characteristics, such as age, condition, shape, construction method, and so on. The range of inspection frequencies in tunnels varies from one week to six years, and some agencies did not provide this information. The most common inspection manual used by transit agencies is the Federal Highway Administration (FHWA)/Federal Transit Administration (FTA) Tunnel Inspection Manual. Other manuals used by transit agencies include the Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual, Department of Transportation (DOT) Inspection Manual, and Agency Standards.

Five transit agencies were selected to visit and to discuss their current practices related to new tunnel design and inspection and maintenance of existing tunnels. The following transit agencies were visited: San Francisco Bay Area Rapid Transit (BART), Los Angeles County Metropolitan Transportation Authority (LA Metro), MTA-New York City Transit Authority (NYCTA), Massachusetts Bay Transportation Authority (MBTA), and Washington Metropolitan Area Transit Authority (WMATA). Some visits focused on new tunnel design and others on the inspection and maintenance of existing tunnels and rehabilitation/retrofit. Topics discussed for new structures included geotechnical aspects, structural type, and challenges during construction. The discussion for existing tunnels focused on the inspection techniques and frequencies, common inspection findings, and recommendations for new design tunnels.

The literature review, site visits, and data collection support analysis of the needs and gaps in rail transit tunnel design, construction, maintenance, and rehabilitation standards. Summary tables are provided for each main topic and available standards, guidelines, and reports.

Section 1

Introduction

Railroad tunnels are an integral part of the rail transit industry and critical for the movement of passengers and freight commodities across cities in the U.S. They are alternatives for crossing under a body of water or traversing through physical barriers such as mountains, existing roadways, railroads, or facilities. In addition, tunnels are a viable means to minimize potential environmental impacts from traffic congestion, such as air quality, noise pollution, or visual intrusion; to allow alternatives for pedestrian movement; to protect areas of special cultural or historical value, such as conservation of districts, buildings, or private properties; or for other sustainability reasons, such as avoiding the impact on the natural habitat or reducing disturbance to surface land.

However, the existing tunnel infrastructure inventory consists of many tunnels exceeding 100 years of age and represents choke points that can produce severe disruption to passenger mobility if a fire or security incident occurs. Tunnels also represent significant financial investments with challenging design, construction, and operational issues. Planning for a tunnel requires multiple-disciplinary involvement and assessments. In many cases, the uniqueness of tunnels leads to specialized research studies for each individual project, especially geotechnical investigations of ground conditions, which are critical for proper planning of a tunnel. For example, the selection of alignment, cross-section, and construction methods is influenced by the geological and geotechnical conditions, as well as the site constraints that will always be unique for a specific project.

Life expectancies of tunnels are significantly longer than those of track components or roads. Therefore, special attention should be dedicated to inspection and maintenance. Tunnel inspection requires multiple-disciplinary personnel familiar with the various functional aspects of a tunnel, including civil/structural, mechanical, electrical, drainage, and ventilation, as well as some operational aspects such as signals, communication, fire-life safety, and security. If the inspection finds any issues within a tunnel structure or supporting systems, simple to more complex maintenance processes must be performed. If large-scale repairs and upgrades are required, the tunnel will be subject to a complex retrofit or rehabilitation project.

This research was undertaken to determine which standards, guidelines, and manuals exist for rail transit tunnels, to identify current gaps of knowledge, and to develop rail tunnel recommendations for the transit industry. Task One focused on the literature review and compilation of existing standards, guidelines, and recommended practices, and Task Two focused on knowledge gaps and potential recommendations.

Section 2

Industry Need

This section includes a list of general industry needs identified through the review of available reports and recommendations from previous tunnel incidents and discussions with transit agencies. While the scope of the subsequent literature review will be more extensive than that addressed in this section, identifying transit agency needs regarding tunnels provides direction and insight into potential knowledge gaps.

The compilation includes available reports published by the National Transportation Safety Board (NTSB) and other U.S. and European agencies. These reports generally involve rare but high-risk events, such as fires and flooding, and emphasize public safety. A summary of the day-to-day operational needs identified through discussions with U.S. transit agencies is also included.

NTSB Reports

NTSB investigated the following three tunnel incidents. While passenger rail is the focus of the report, freight rail and roadway incidents are also included due to the low amount but high impact nature of tunnel incidents. Each description contains a summary of the incident and corresponding NTSB recommendations.

WMATA L'Enfant Plaza Station Smoke Accident (NTSB 2016)

On January 12, 2015, the Washington Metropolitan Area Transit Authority (WMATA) had an electrical arcing and smoke accident between the L'Enfant Plaza station and the Potomac River in Washington, DC.[3] Train 302, with about 380 passengers onboard, stopped in the tunnel after encountering heavy smoke and was unable to return to the station before losing power to the electrified third rail. Some passengers on Train 302 self-evacuated and others were assisted by first responders from the District of Columbia Fire Department and Emergency Medical Services. The incident resulted in 1 fatality, 91 injuries, and $120,000 of property damage. The NTSB investigated the incident and published a report on May 3, 2016.

The probable cause of the incident was summarized in the report as follows:

> The National Transportation Safety Board determines that the probable cause of the Washington Metropolitan Area Transit Authority (WMATA) L'Enfant Plaza station electrical arcing and smoke accident was a prolonged short circuit that consumed power system components resulting from the WMATA's ineffective inspection and maintenance practices. The ineffective practices

---

[3] NTSB (National Transportation Safety Board), *Washington Metropolitan Area Transit Authority L'Enfant Plaza Station Electrical Arcing and Smoke Accident*, NTSB/RAR-16/01. Washington, DC, 2016.

> persisted as the result of (1) the failure of the WMATA senior management to proactively assess and mitigate foreseeable safety risks, and (2) the inadequate safety oversight by the Tri-State Oversight Committee and the Federal Transit Administration. Contributing to the accident were WMATA's failure to follow established procedures and the District of Columbia Fire and Emergency Medical Services Department's being unprepared to respond to a mass casualty event on the WMATA underground system.

Specific issues that led to or exacerbated the problem included:

- Electrical arc tracking due to improperly constructed power cable connector assemblies and aided by the presence of contaminants and moisture.
- Water intrusion had been ongoing prior to the accident.
- Tunnel washing and insulator cleaning was discontinued prior to the accident.
- The train entered the tunnel 10 minutes after the smoke detector in the tunnel activated and 7 minutes after another train reported smoke in the tunnel.
- Ventilation fans were not operated until 10 minutes after train stoppage and multiple defective fan components prevented optimal removal of smoke, leaving only two of four fans working. Additionally, the WMATA Rail Operations Control Center (ROCC) train control operators were not trained on strategies for the proper use of fans.
- Ventilation systems in the train were not properly turned off, allowing smoke to enter train cars. No procedure was developed for this event.
- A lack of emergency lighting in the tunnel and conduit and junction boxes on the tunnel wall above the walkway were safety hazards to passengers evacuating through the tunnel.

Due to this incident, several safety recommendations were made to multiple parties, including FTA, U.S. Department of Transportation (USDOT), American Public Transit Association (APTA), WMATA, the mayor of the District of Columbia and its office of unified communications, and the fire and emergency medical services department.

The following safety recommendations were made to FTA:

- R-15-7: Audit all rail transit agencies that have subway tunnel environments to (1) assess the state of repair of tunnel ventilation systems, (2) assess written emergency procedures for fire and smoke events, (3) assess training programs to ensure compliance with these procedures, and (4) verify that rail transit agencies apply industry best standards, such as the National Fire Protection Association (NFPA) 130,[4] *Standard for Fixed Guideway Transit and Passenger Rail Systems*, in maintenance procedures and emergency procedures.

- R-16-01: Issue regulatory standards for tunnel infrastructure inspection, maintenance, and repair, incorporating applicable industry consensus standards into those standards.
- R-16-02: Issue regulatory standards for emergency egress in tunnel environments.

The safety recommendations given to the other parties primarily consisted of ensuring supporting systems are in good repair, developing inspection and maintenance practices, installing new fire and smoke detection systems, and coordinating communication of various parties during an emergency. The responses have not yet been judged by NTSB and are considered open.

In a national public safety plan,[5] FTA addresses part of NTSB recommendation R-15-7 by highly recommending that transit agencies follow the NFPA 130[6] standards along with Recommended Fire Safety Practices for Rail Transit Materials Selection.[7]

Howard Street Tunnel Fire (NTSB 2004)

On July 18, 2001, a CSX freight train derailed 11 of 60 cars while passing through the Howard Street Tunnel in Baltimore, Maryland.[8] The derailed cars consisted of four tank cars and one carrying tripropylene (a highly flammable gas used in cleaning agents, lubricants, and oils) was punctured and caught on fire. The fire spread to surrounding cars creating heat, smoke, and fumes that prevented tunnel access for several days and caused a water main located above the tunnel to break, flooding the tunnel with millions of gallons of water. The total cost of the accident was estimated at $12 million, and the initial cause of the derailment is unknown.

Some potential derailment scenarios were suggested, including sand in the tunnel, wide-gauge track, track geometry, and track structure defects. Water intrusion was also considered a potential factor. Recommendations to CSX included maintaining historical documentation of maintenance activities affecting the Howard Street Tunnel and increasing coordination with the

---

[4] NFPA, *NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems*, Quincy, MA, 2017.

[5] FTA, National Public Transportation Safety Plan, Washington DC, 2017.

[6] NFPA 130, *op. cit*.

[7] USDOT (U.S. Department of Transportation), *Recommended Fire Safety Practices for Rail Transit Materials Selection*, Washington, DC, 1998. https://www.transit.dot.gov/regulations-and-guidance/safety/recommended-fire-safety-practices-rail-transit-materials-selection.

[8] NTSB, CSX Freight Train Derailment and Subsequent Fire in the Howard Street Tunnel in Baltimore, Maryland, on July 18, 2001, Railroad Accident Brief, NTSB/RAB-04/08, Washington, DC, 2004.

City of Baltimore. One of the recommendations to the City was to update emergency preparedness documents to include hazardous materials discharge response procedures specific to tunnel environments, as well as infrastructure information on the Howard Street Tunnel. The majority of the responses by CSX and the City of Baltimore were deemed acceptable.

While the fire occurred on a freight line carrying material that would not be present along transit lines, the need for maintenance records and emergency preparedness is relevant to all types of tunnels and crisis situations.

Bay Area Rapid Transit District Fire (NTSB 1979)

On January 17, 1979, two cars on a Bay Area Rapid Transit (BART) transit train caught fire while moving through a tunnel under San Francisco Bay.[9] Forty-two individuals were evacuated from the burning train through emergency doors into the gallery walkway located between the two single-track tunnels and into a waiting train in the adjacent tunnel. The incident resulted in 1 fatality of a firefighter, 44 smoke-related injuries, and $2,450,000 of property damage. NTSB investigated the incident and published a report on July 19, 1979.

The NTSB investigation determined the probable cause of the accident was the breaking of a collector shoe assembly on the train when it struck a line switch box cover, which had fallen from an earlier train. The report also mentioned inadequate coordination between BART and the Oakland and San Francisco fire departments, inadequate following of an emergency response plan, a lack of passenger carbody design to limit or prevent fire from entering the interior, the release of smoke from the tunnel into the gallery walkway from open doors, and the plastic materials used in the construction of the transit cars produced heavy smoke and toxic fumes.

NTSB made several recommendations to the BART district, APTA, and Urban Mass Transportation Administration (UMTA) (currently FTA), including but not limited to:

- R-79-42: Revise emergency procedures to clarify the necessity of unloading passengers immediately from a stopped burning train in the Transbay Tube and other long tunnel locations.
- R-79-44: Revise Transbay Tube emergency fan and damper procedures to prevent smoke from engulfing an entire train and/or entry into the gallery.
- R-79-53: Review and revise as necessary vehicle inspection procedures and emergency evacuation guidelines for APTA members to correct deficiencies noted in this investigation.

---

[9] NTSB, Bay Area Rapid Transit District Fire on Train No. 117 and Evacuation of Passengers while in the Transbay Tube, Railroad Accident Report, NTSB-RAR-79-5, Washington, DC, 1979.

- R-79-54: Promulgate regulations establishing minimum fire safety standards for the design and construction of rapid transit vehicles.

Other recommendations involved addressing the cause of the fire, upgrading transit materials to better resist fire, and modifying the emergency response plan with the Oakland and San Francisco fire departments. NTSB deemed that the BART district responded acceptably to R-79-42 and R-79-44 and that APTA responded acceptably to R-79-53. The UMTA reaction to R-79-54 was deemed unacceptable. As an author note, the development of NFPA 130[10] (dated 2017 and first published in 1990) addresses many of these issues and is used currently by many transit agencies.

Other Notable Tunnel Incidents

This section addresses other incidents that were either not investigated by NTSB or occurred in countries other than the United States. Both railway and roadway tunnel incidents are included.

Road Tunnel Fires

Multiple road tunnel fires between 1999 and 2001 contributed to the push for tunnel safety assessment in Europe. These fires occurred in tunnels that connected two European countries in which the length of the tunnels and the difficulty of responder communication contributed to delayed emergency response.

- On March 24, 1999, the Mont Blanc Tunnel fire resulted in 39 fatalities and many injuries due to a fire originating in a truck carrying flour and margarine. The Mont Blanc Tunnel is a 7.3-mile (11.6-km) single-bore tunnel with bidirectional traffic that connects France and Italy. The truck in which the fire started stopped in the tunnel and the temperature quickly rose to 1,832°F (1,000°C). Both fire detection systems were delayed from a lack of alarm on the French side and a turned-off alarm on the Italian side due to false alarm issues. The airflow in the tunnel was believed to be traveling from Italy to France, allowing truckers and passengers on the Italian side to escape but engulfing the French side in toxic smoke. An Italian operator decided to introduce oxygen instead of extraction, which fueled the fire and compounded the adverse effects on the French side. Another contributing factor was known ventilation deficiencies that had not been repaired before the incident.
- On May 29, 1999, a fire in the Tauern Road Tunnel resulted in 12 fatalities and 42 injuries. The Tauern Road Tunnel is a 4-mile (6.5-km) single-bore tunnel in Austria. The fire started due to collision between a truck and a stationary vehicle waiting at a traffic signal. This incident eventually

---

[10] NFPA 130, *op cit*.

involved 60 vehicles. Investigations suggest eight victims died from the collision and four died from the fire.

- On October 24, 2001, the St. Gotthard Tunnel fire resulted in 11 fatalities and many injuries. The St. Gotthard Tunnel is a 10.6-mile (17-km) single-bore tunnel with bidirectional traffic that connects two towns in Switzerland. The fire started when a truck collided with another truck carrying tires, igniting the tires and leading to toxic black smoke and temperatures reaching 1,832°F (1,000°C). An investigation found the safety systems worked well, and recommendations were made to reduce traffic flows through the tunnel.

Partly due to these fires, the European Union passed directive 2004/54/EC on April 29, 2004,[11] on road tunnel safety. Additionally, the European Union passed directive 2008/168/EC on safety in railway tunnels on July 3, 2008, and it was updated November 18, 2014, with Commission Regulation No. 1303/2014.[12]

Channel Tunnel Fires (United Kingdom/France)

The Channel Tunnel, a 32-mile (50-km) tunnel connecting the United Kingdom and France, has experienced multiple fires since being put into service, with three notable fires occurring in 1996, 2006, and 2008. The tunnel is the longest undersea tunnel and consists of three bores; the two outside tunnels accommodate rail traffic and the middle tunnel is used as an emergency escape route.

The 1996 and 2008 fires closed the Channel Tunnel for 7 and 16 hours, respectively. Both incidents occurred on trains carrying heavy goods vehicles and resulted in minor passenger injuries due to smoke inhalation. The 2006 fire resulted in a minor shutdown time. The authors of this report are unaware of any action taken in response to these fires. The lack of fatalities during the tunnel fires was partially attributed to the three-tunnel layout of the Channel Tunnel, as opposed to a single-tunnel system such as the Mont Blanc, Tauern Road, and St. Gotthard Tunnels.

Gerrards Cross Tunnel (Buckinghamshire, England)

On June 30, 2005, the Gerrards Cross Tunnel near Buckinghamshire, England, collapsed during construction. No trains were in the tunnel during the collapse, but it could have resulted in dozens, if not hundreds, of deaths if the collapse had occurred at a different time. The cause of the collapse was attributed to uneven backfilling, which created higher loads on the crown and not enough fill on the sides.

---

[11] EU, Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network. Brussels, Belgium, 2004.

[12] EU 1303/2014, *op. cit*.

The authors of this report are unaware of any push for additional regulations after the incident; however, it gives an example of how improper construction techniques can result in tunnel collapses.

Tunnel Security Incidents

Multiple tunnel security incidents have also occurred in past decades from terrorist attacks. These incidents can be especially catastrophic because of the preplanned nature and motivation to affect the maximum number of people.

- The July 7, 2005, London bombings were a series of coordinated terrorist suicide bomb attacks in London, United Kingdom, targeting civilians traveling on the city's public transport system during the morning rush hour. Four Islamic terrorists separately detonated three bombs in quick succession aboard London Underground trains across the city and later detonated a fourth bomb on a double-decker bus in Tavistock Square. The train bombings occurred on the Circle Line near Aldgate and Edgware Road and on the Piccadilly line near Russell Square. Fifty-two people were killed and more than 700 were injured in the attacks, making it Britain's deadliest terrorist incident since the 1988 bombing of Pan Am Flight 103 over Lockerbie, Scotland, as well as the country's first-ever Islamist suicide attack.
- On February 6, 2004, a bomb linked to Chechen separatists exploded inside a crowded Moscow subway station during morning rush hour. The incident involved 39 fatalities and more than 100 injuries. The incident resulted in enhanced security in Moscow and other Russian cities.
- On February 18, 2003, a suspected suicide from self-immolation produced an arson fire in the Jungangno Subway Station in Daegu, South Korea. The incident started with a mentally unstable man throwing flammable liquid inside a subway car and igniting it. The fire spread due to flammable seats and other internal furnishings. A power failure trapped passengers inside the remaining five cars. The incident resulted in 198 fatalities, 147 injuries, and more than 50 people missing. In response, the South Korean president promised to install emergency lighting, increase the number of exit signs, make car interiors flame resistant, and heighten security.
- On March 20, 1995, a sarin gas attack was coordinated by religious extremists in Tokyo, Japan. The incident involved 12 fatalities and the exposure of 5,000 to 6,000 people to sarin gas. The attack was coordinated by 10 people working in two groups to release the gas on five trains. The religious sect had enough gas to kill 4.2 million people, but the subway network air filtering system attributed to limiting the fatalities to 12.

Tunnel Flooding

Tunnel flooding from rainstorms, hurricanes, or dam breaks can cause damage exceeding billions of dollars. In recent decades, two significant subway flooding events occurred in the United States: the Chicago flood in 1992 and Hurricane Sandy in New York City in 2012 (DHS 2014).[13]

The Chicago flooding was caused by piling driven into the Chicago River bottom producing a leak in the tunnel causing damage to city property estimated at nearly $2 billion. The damage from flooding due to Hurricane Sandy is estimated to be tens of billions of dollars.

Subway and tunnel flooding is considered a significant risk in the upcoming century due to rising seawater levels and the number of subway systems near coastal areas. High-risk storms such as Hurricane Sandy are anticipated to become more common in the upcoming century, so prevention measures and technologies are important for mitigating the damage from these increased risk events.

Discussions with Transit Agencies

The incidents previously listed typically involve fire and other scenarios that require emergency response. Because they directly involve the safety of passengers, employees, and emergency responders, they often result in regulatory standards. These can include but are not limited to:

- Use of materials that can withstand fire temperatures and not contribute to toxic smoke and gases
- Adequate installation of ventilation and agency employee knowledge of best practices for ventilating tunnels during fire, smoke, or gas incidents
- Adequate measures to ensure passenger egress from tunnels and emergency responder access points
- Adequate emergency response plans for agencies and emergency responders and proper communication between these parties
- New technologies to mitigate against flooding risks

While emergency response in rare but high-risk events is a significant focus, the industry has additional daily operational needs. The following list was compiled based on discussions with U.S. transit agencies:

- Inspection and maintenance guidelines that agencies can use for tunnel structure integrity and supporting systems
- Dynamic movement from train vibrations or seismic events
- New technologies that can be implemented to improve tunnel safety and that could be used for inspections

---

[13] DHS (U.S. Department of Homeland Security), *Resilient Tunnel Project*, DHS Science and Technology Directorate 508, July 2014.

Section 3

Review of Tunnel Literature

This section presents a literature review of existing U.S. and international standards, guidelines, and recommendations regarding transit tunnels. The objective is to determine what standards exist, how different standards compare, and to identify current knowledge gaps.

The project team compiled multiple sources to understand existing standards, guidelines, and recommended practices. These sources include roadway tunnel standards and standards from international sources, as both are relevant to railway tunnel standards in the United States.

The literature review is divided into six sections based on the topics:

- Tunnel Structural Design
- Tunnel Construction
- Tunnel Supporting Systems
- Tunnel Security and Risk Assessment
- Tunnel Maintenance and Inspection
- Tunnel Rehabilitation

The tunnel structural design section covers geotechnical investigations of ground conditions, geometrical requirements, and cross-section elements. Many methods for structural design and materials are available and are described in this section. All applicable loads and load combinations needed for structural design are also listed.

The construction section covers common construction methods: cut-and-cover, shield driven, bored, jacked, immersed tube, drill and blast, and Sequential Evacuation Method (SEM). Additional aspects of construction, such as temporary support and ventilation during the construction, are also described.

Tunnel supporting systems play a significant role in ensuring the safety of passengers, personnel, and emergency responders inside a tunnel during an incident. Supporting systems include but are not limited to fire detection, ventilation, and passenger egress. This section and the tunnel security and risk assessment section overlap because supporting systems are often required for security and emergency response.

The tunnel security and risk assessment section describes agency planning for and response to incidents instead of the equipment that will be used (supporting systems). This also incorporates security and emergency response.

The tunnel maintenance and inspection section covers maintenance activities, inspection requirements, procedures for inspection reports, and tunnel evaluation. It also describes potential issues within a tunnel and repair methods.

Tunnel Structural Design

Railway tunnel design incorporates the initial planning and design stages of tunnel construction. Many structural design methods and materials are available, but all structures must be designed for specified limit states considering all applicable loads and load combinations.

Tunnel design is strongly dependent upon the geological setting, site conditions, and construction methodology. The ground/structure interaction is important in the design process. According to the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD), tunnels should 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:[14]

The specified 150-year design life is appropriate for the design of tunnel geotechnical features and soil-structure-interaction-systems given 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.

According to LA Metro Rail Design Criteria and New York City Transit Authority (NYCT) Structural Design Guidelines DG452a, the tunnel structures are to be designed for 100 years. The criteria that must be met include crack width and crack control, concrete composition, waterproofing, and corrosion control of rebar and structural steel.

The AASHTO LRFD tunnel structural components should satisfy the following limit states:[15]

- The *service limit state* as restriction on stress, deformation, and crack width under regular service conditions.
- The *fatigue and fracture limit state* as restriction on stress range as a result of repetitive machinery or ventilation loads at the number of expected stress range cycles.

---

[14] AASHTO (American Association of State Highway and Transportation Officials), LRFD Road Tunnel Design and Construction Guide Specifications, Publication Code LRFDTUN-1, First edition, 2017.

[15] *Ibid*.

- The *strength limit state* 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.
- The *extreme event limit state* 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 vessels or anchor drag loads possibly during, or in conjunction with, a scour event.

According to AASHTO LRFD, the selection of the type of tunnel should be based on the geometrical configurations, ground conditions, type of crossing, and environmental requirements. The choice for a tunnel location should be supported by an analysis of alternatives, which is typically completed during the planning and National Environmental Policy Act phase of tunnel projects.

Geotechnical Exploration/Investigation

The first step for railway tunnel design will always be geotechnical investigation of ground conditions. Geotechnical investigations are critical for proper planning of a tunnel. Selection of the alignment, cross-section, and construction methods is influenced by the geological and geotechnical conditions, as well as the site constraints. Knowledge of the expected geological conditions is essential.

The Federal Highway Administration (FHWA) *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*[16] presents what should be considered for the selection of the tunnel profile:

- Avoid locations where potential ground movements or settlements could cause surface problems to existing utilities or surface facilities. Mitigation measures should be accounted for.
- Be aware of the presence of active or inactive faults.
- Consider the soil and rock properties and their anticipated behaviors during excavation.
- Consider the presence of contaminated materials, special existing buildings and surface facilities, existing utilities, or the presence of sensitive installations such as historical landmarks, educational institutions, cemeteries, or houses of worship.

American Railway Engineering and Maintenance-of-Way Association (AREMA) *Manual for Railway Engineering* (Chapter 1, Part 8)[17] specifies the following common practices:

---

[16] FHWA (Federal Highway Administration), *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*, Publication No. FHWA-NHI-10-034, December 2009.

[17] AREMA (American Railway Engineering Maintenance-of-Way Association), *Manual for Railway Engineering*, Chapter 1 – Roadway and Ballast, Part 8 – Tunnels, 2017.

- Geotechnical Data Report (GDR)
- Geotechnical Baseline Report (GBR)
- Geotechnical investigation
- Soil sampling and rock coring
- Horizontal directional coring
- Pilot tunnel
- Field testing
- Laboratory testing
- Rock mass classification and analysis

FHWA's technical manual for tunnels[18] and AASHTO's LRFD road tunnel guide[19] provide phases of the geotechnical investigation program:

- Phase 1 – Information Study
- Phase 2 – Surveys and Site Reconnaissance
- Phase 3 – Geologic Mapping
- Phase 4 – Subsurface Investigations
- Phase 5 – Environmental Issues
- Phase 6 – Seismicity
- Phase 7 – Additional Investigations during Construction
- Phase 8 – Geospatial Data Management System

Geotechnical reports required for planning, design, and construction of road tunnels, including GDR, presents all the factual geotechnical data; Geotechnical Design Memorandum (GDM), presents interpretations of the geotechnical data and other information used to develop the designs; and GBR defines the baseline conditions on which contractors will base their bids. Applicable manuals and guidelines for geotechnical exploration and investigation are listed in Table 3-1.

---

[18] FHWA-NHI-10-034, *op. cit*.
[19] AASHTO LRFDTUN-1, *op cit*.

Table 3-1 *Applicable Manuals and Guidelines for Geotechnical Exploration and Investigation*

Document	Applicability
FHWA-NHI-10-034, December 2009, *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*	Direct application
AASHTO *LRFD Road Tunnel Design and Construction Guide Specifications*, First Edition, 2017	Direct application
AREMA Manual for Railway Engineering, Chapter 8, Part 11 – Lining Railway Tunnels	Direct application
Essex, Randall J. *Geotechnical Baseline Reports for Underground Construction: Guidelines and Practice*. New York: ASCE, 1997	Supplementary information
Raines, Gregory L. *Geotechnical Investigations for Mechanical Tunneling. American Society for Civil Engineering*.	Supplementary information
International Society for Rock Mechanics (ISRM). Bedrock Classification System. *Basic Geotechnical Description of Rock Masses*, 1980.	Supplementary information
International Society for Rock Mechanics (ISRM). Bedrock Classification System. "Suggested Methods for the Quantitative Description of Discontinuities in Rock Masses," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 15: 319–68. 1977.	Supplementary information
U.S. Army Corps of Engineers. *Geophysical Exploration for Engineering and Environmental Investigations*. EM 1110-1-1802, August 1995.	Supplementary information
U.S. Army Corps of Engineers. *Geotechnical Investigations*. EM 1110-1-1804, January 2001.	Supplementary information
U.S. Army Corps of Engineers. *Laboratory Soils Testing*. EM 1110-2-1906, November 1980, updated August 1986.	Supplementary information
U.S. Army Corps of Engineers. *Soil Sampling*. EM 1110-1-1906, September 1996.	Supplementary information
U.S. Federal Highway Administration. *Geotechnical Earthquake Engineering*. FHWA H1-99-012, December 1998.	Supplementary information
U.S. Federal Highway Administration. *Geotechnical Instrumentation*. FHWA H1-98-034, October 1998.	Supplementary information
U.S. Federal Highway Administration. *Subsurface Investigations*. FHWA HI-97-021, November 1997.	Supplementary information

Geometrical Requirements and Clearance

The geometrical requirements and recommendations of new road/rail tunnels include horizontal and vertical alignments and tunnel cross-section requirements. Clearances for railway tunnels will be dependent on tunnel shape, car type, widths of drainage ditches, escape walkways, track separation, and track curvature.

FHWA-NHI-10-034[20] describes all cross-section elements for road tunnels, including:

- Travel Lane and Shoulder
- Sidewalks/Emergency Egress Walkway
- Tunnel Drainage Requirements
- Ventilation Requirements
- Lighting Requirements
- Traffic Control Requirements
- Portals and Approach

AASHTO LRFD[21] specifies that a minimum walkway width of 3 ft 6 in (1.07 m) should be provided outside the shoulders or, when no shoulders are present, outside the roadway. The walkway should be raised above the roadway by a minimum of 6 in (0.15 m) to be protected from oncoming traffic. The requirements of NFPA 502[22] must be considered when dimensioning shoulders and walkways.

The *AREMA Manual*[23] does not provide recommendations, leaving it up to the designers to ensure the clearance is sufficient for the specific tunnel. It does provide a minimum standard for both single and double track (Figure 3-1).

---

[20] FHWA-NHI-10-034, *op. cit*.
[21] AASHTO LRFDTUN-1, *op. cit*.
[22] NFPA 502, *op. cit*.
[23] AREMA Manual 2017, Chapter 1, *op. cit*.

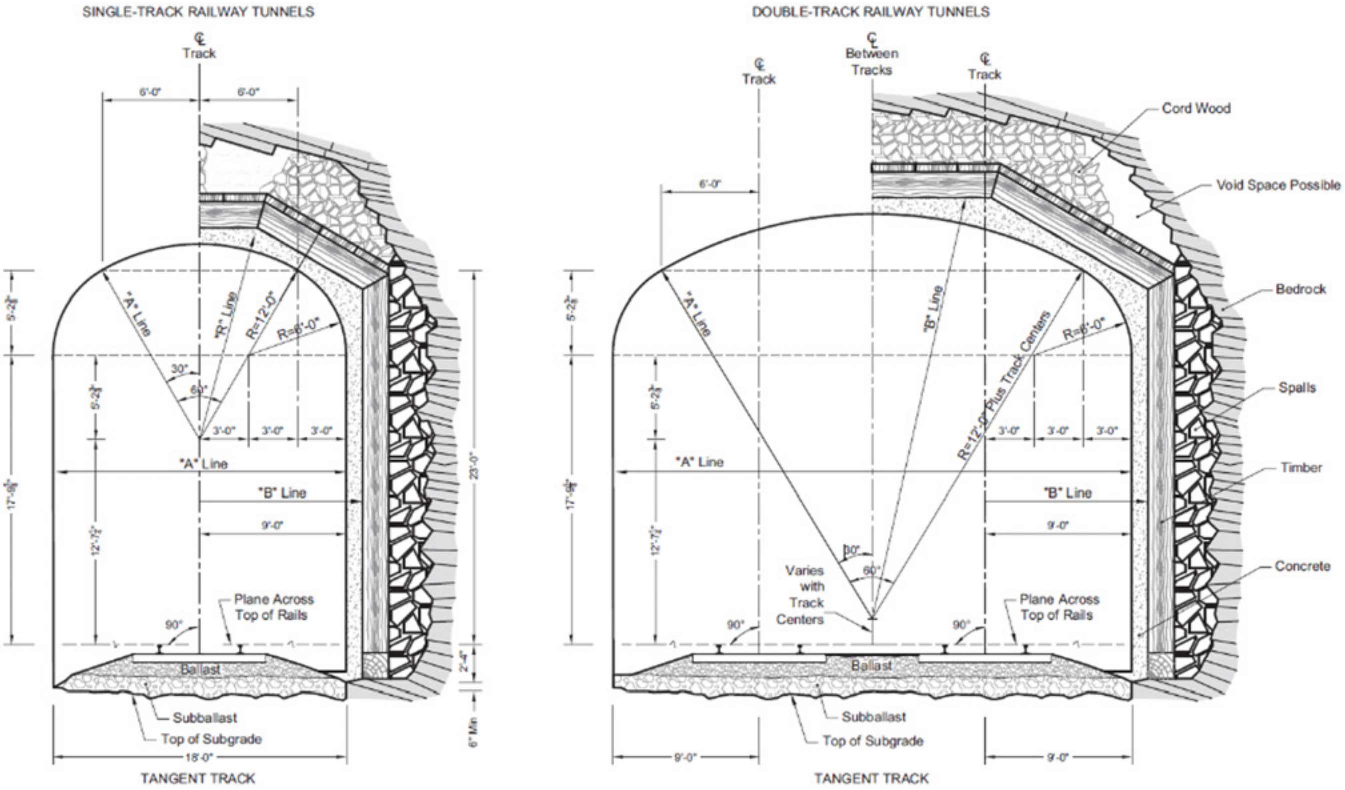


Figure 3-1 *Single and double track railroad tunnels (AREMA)*[24]

The European Union Safety in Railway Tunnels – Technical Specification for Interoperability (SRT TSI)[25] Section 4.2.16 states that a width of 2 ft 7.5 in (0.8 m) and clearance of 7 ft 4.5 in (2.25 m) for escape walkways be considered during tunnel geometric design.

Load and Load Combinations

The tunnel structures should be designed for specified limit states considering all applicable loads and load combinations. AASHTO LRFD[26] defines all the load factors for various loads comprising a load combination. Table 3-2 lists load designations and Table 3-3 describes load combinations per AASHTO LRFD.

---

[24] *Ibid*.

[25] EU 1303/2014, *op. cit*.

[26] AASHTO LRFDTUN-1, *op. cit*.

Table 3-2 *Load Designations (AASHTO LRFD)*

Permanent Loads	Transient Loads
CR = force effects due to creep DC = dead load of structural components and nonstructural attachments DW = dead load of wearing surfaces and utilities EH = horizontal earth pressure load ES = earth surcharge including foundation surcharges EV = vertical pressure from soil and rock tunnels PI = loads due to piping systems inside the tunnel PS = secondary forces due to post-tensioning SE = effect of settlement of tunnel structure SH = force effects due to shrinkage	AD = anchor drop AP = air pressure BL = force effect due to blast BR = vehicular braking force CE = vehicular centrifugal forces CS = construction loading EQ = earthquake load FI = force effect due to fire IA = attachment dynamic load allowance IM = vehicular dynamic load allowance LL = vehicular live load LS = live load surcharge PL = pedestrian live load LS = live load surcharge PL = pedestrian live load SS = ship sinking TG = force effect due to temperature gradient TU = force effect due to uniform temperature WA = water load WAf = water load due to flooding WAt = transient water load Wtsu = water load due to tsunami

Table 3-3 *Load Combinations (AASHTO LRFD)*

Load Combinations (AASHTO LRFD)	
Strength T-I	Basic load combination relating to permanent ground loading conditions that develop over time after the completion of construction, and to the normal vehicular use of structure.
Strength T-II	Load combination relating to the temporary ground loads imposed during tunnel excavation. Also related to construction imposed loading on segmental tunnel linings and immersed tunnel segments during fabrication, transportation, handling, and erection or placement.
Extreme Event T-I	Load combination including earthquake.
Extreme Event T-II	Load combination relating to ship grounding/sinking, anchor drop, flood, tsunami, blast, or fire.
Extreme Event T-III	Load combination relating to flood or tsunami used to check the resistance of the underground construction to the effects of buoyancy.
Service T-I	Load combination relating to permanent ground loading conditions that develop over time after completion of construction and the normal vehicular use of the structure.
Service T-IA	Load combination relating to service level water loads used to check the resistance of the underground construction to the effects of buoyancy.
Service T-II	Load combination relating to the temporary ground loading conditions that develop during construction.
Fatigue T-I	Fracture and fatigue load combination related to infinite load-induced fatigue life.

LA Metro Rail specified more load cases within the Live Load LL group that are specific for rail tunnels:

- Weight of heavy rail vehicle (HRV)
- Weight of heavy rail crane car (HP)
- Weight of light rail vehicle (LRV)
- Weight of light rail maintenance car (LP)

Also, other specifics to the rail operation load were defined, such as:

- Derailment loads (DR)
- Dynamic load allowance (IMV, IMH)
- Centrifugal force (CE)
- Longitudinal force (LF) due to acceleration and deceleration (for example, emergency braking and BR), restraint of continuous welded rail (CWR), and rail bumping posts
- Down drag force (DD)
- Rail fracture (RF)
- Railroad or vessel collision load (CV)

Table 3-4 describes load combinations used in the LA Metro Rail standard.

Table 3-4 *Load Combinations (LA Metro Rail)*

Strength I	Load combination relating to operational use of the guideway without wind.
Strength II	Load combination relating to use of owner-specified permit vehicles without wind.
Strength III	Load combination relating to non-operational use of the guideway with high velocity wind.
Strength IV	Load combination relating very high dead load to live load force effect ratios.
Strength V	Load combination relating to operational use of the guideway with operational wind.
Strength VI	Load combination relating to operational use of the guideway with emergency braking (BR).
Extreme Event I	Load combination relating to operational use of guideway during the maximum design earthquake (MDE) seismic event for connection of superstructure to substructure only (See Metro SSDC).
Extreme Event IA	Load combination relating to operational use of the guideway with the operational design earthquake (ODE). See Appendices A and B.
Extreme Event II	Load combination relating to operational use of guideway during a vehicle or a railroad collision (CT). (Vehicle and railroad collisions are considered separate events and should not be applied simultaneously. See Section 5.2.16)
Extreme Event III	Load combination relating to operational use of the guideway during a derailment.
Extreme Event IV	Load combination relating to a rail fracture.
Service I	Load combination relating to operational use of the guideway with operational wind.
Service II	Load combination intended to control yielding of steel structures and slip of slip-critical connections due to live load.
Service III	Load combination for longitudinal analysis relating to tension in prestressed concrete structures with the objective of crack control and to principal tension in the webs of segmental concrete girders.

Service IV	Load combination relating only to tension in prestressed concrete substructures with the objective of crack control.
Service V	Load combination relating only to control of uplift and concrete tension during derailment.
Service VI	Load combination relating only to segmental bridges, with no live loads and full temperature gradient.
Fatigue I	Fatigue and fracture load combination relating to repetitive live load and dynamic response for transit and roadway vehicles.
Fatigue II	Fatigue and fracture load combination relating to repetitive live load and dynamic response for transit and roadway maintenance and permit vehicles.

LA Metro Rail specified Special Design Considerations for tunnels and, particularly, a vertical vibration section. It recommended performing an analysis of the dynamic interaction between the vehicles and the guideway structure to avoid resonance and provide passenger comfort. The specifications state: “To limit vibration amplification due to the dynamic interaction between the superstructure and the rail car(s), the first-mode natural frequency of vertical vibration of each simple span guideway should generally be not less than 2.5 hertz, and no more than one span in a series of three consecutive spans should have a first-mode natural frequency of less than 3.0 hertz. Special analysis shall be performed for any bridge or for superstructures having a first mode of vertical vibration less than 2.5 hertz or for the condition when more than one span in a series of three consecutive spans has the first mode of vibration less than 3.0 hertz.”[27]

NYCT *Structural Design Guidelines* (DG 452A)[28] defined train axle loads on subway tracks. Also, the guidelines provide tables with maximum values of shear, moment, and floor beam reaction due to train load on various span lengths from 6 to 100 ft (1.8 to 30 m). In addition, the impact and centrifugal forces (if applicable) should be added to the dead load and train load.

Other applicable manuals and guidelines for load and load combinations are listed in Table 3-5 and additional literature addressing structural load is listed in Table 3-6.

---

[27] LA Metro Rail Design Criteria Section 05 Structural/Geotechnical.

[28] NYCT (New York City Transit), *DG 452A Structural Design Guidelines: Subway and Underground Structures, Issue No. 3, November 24, 2015.*

Table 3-5 *Applicable Manuals and Guidelines for Load and Load Combinations*

Document	Applicability
AASHTO *LRFD Road Tunnel Design and Construction Guide Specifications*, First Edition, 2017.	Direct application
LA Metro Rail Design Criteria Section 05 Structural/Geotechnical.	Direct application
NYCT *DG 452A Structural Design Guidelines: Subway and Underground Structures Issue No. 3, November 24, 2015*.	Direct application
Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE/SEI 7-16), American Society of Civil Engineers (ASCE), describes the means for determining dead, live, soil, flood, tsunami, snow, rain, atmospheric ice, earthquake, and wind loads, and their combinations for general structural design.	Supplementary information
Design Loads on Structures during Construction (ASCE/SEI 37-14), American Society of Civil Engineers (ASCE).	Supplementary information
International Existing Building Code and Commentary, International Code Council, ICC IEBC-2015.	Supplementary information
California Building Code, Title 24, Part 2 (Volumes 1 & 2 - Includes Parts 8 & 10), International Code Council, ICC CBC-2016.	Supplementary information
U.S. Army Corps of Engineers (USACE). *Engineering and Design, Tunnels and Shafts in Rock*. EM 1110-2-2901, May 1997.	Supplementary information
Concrete Structures under Impact and Impulsive Loading. Information Bulletin No. 187, International Federation for Structural Concrete, August 1988.	Supplementary information

Table 3-6 *Other Literature That Addresses Structural Load*

Document	Applicability
Barton, N., R. Lien, and J. Lunde. "Engineering Classification of Rock Masses for the Design of Tunnel Support." *Rock Mechanics* 6 (4), 1974.	Supplementary information
Bickel, J. O., T. R. Kuesel, and E. H. King, eds. *Tunnel Engineering Handbook, Second Edition*. New York: Chapman & Hall, 1996.	Supplementary information
Bieniawski, Z. T. *Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering*. New York: Wiley, 1989.	Supplementary information
Choi, Sunghoon. *Tunnel Stability Under Explosion*. New York: Parson Brinckerhoff Incorporated, 2009.	Supplementary information
Russel, H. A. "ITA Guidelines for Structural Fire Resistance of Road Tunnels." *Routes/Roads* 324, October 2004.	Supplementary information

Structural Materials and Design Consideration

Tunnel structural components should be designed to resist load combinations and conform to the requirements of the LRFD specifications. The structural behavior of components constructed from concrete, steel or steel in combination with other materials, and wood should be investigated for each stage that may be critical during construction, handling, transportation, and erection, as well as during the service life of the structure of which they are a part.

LA Metro Rail Design Criteria[29] provide details about structural materials, for example:

- Minimum compressive strength of concrete to be 4,000 psi (27.6 MPa) for aboveground and underground reinforced concrete cast-in-place structures; 6,000 psi (41.4 MPa) for prestressed concrete; 5,000 psi (34.5 MPa) for precast prestressed concrete members.
- Reinforcing steel must conform to AASHTO M 31 for billet steel bars or ASTM A706 for low-alloy steel bars and additional requirements listed.
- Prestressing steel strand ASTM A416 (AASHTO M 203) (low relaxation), high strength steel bar ASTM A722 (AASHTO M 275).
- Refer to AISC *Manual of Steel Construction: Load and Resistance Factor Design*,[30] latest edition, Specification for Structural Joints Using ASTM A325 or A490 Bolts for use of bolts in snug-tightened, pretensioned, and slip critical joint applications.
- Structural steel channels, angles, MC shapes: ASTM A36 or ASTM A50, structural steel W shapes for building frame: ASTM A992; structural steel tube: ASTM A500 Gr B; structural steel pipe: ASTM A53 Gr B; for uses requiring higher steel strengths or where economically justifiable: ASTM A242, A441, A514, A572, A588.

Similar requirements are provided in NYCT Structural Design Guidelines,[31] for example:

- Minimum compressive strength of cast-in-place concrete should be 4,000 psi (27.6 MPa), and for precast concrete should be 5,000 psi (34.5 MPa).
- Minimum compressive strength of shotcrete concrete should be 4,000 psi (27.6 MPa), and for fill materials concrete should be 2,000 psi (13.8 MPa).
- Reinforcing steel must conform to ASTM A706 or ASTM A615, Grade 60.
- Structural steel channels, angles, MC shapes: ASTM A36 or ASTM A572, structural steel W shapes for building frame: ASTM A992; structural steel tube: ASTM A500 Gr B; structural steel pipe: ASTM A53 Gr B; structural plate: ASTM A36, A572, A786, A606, A607, A653.
- Steel to steel fastening should be ASTM A325 or A490 bolts. Additional details are provided for nuts, washers, threaded rods, and steel studs.

Other applicable manuals and guidelines for structural materials are listed in Table 3-7.

---

[29] LA Metro Rail, *op. cit*.

[30] AISC (American Institute of Steel Construction), *Steel Construction Manual: Load and Resistance Factor Design, Third edition*, 2001.

[31] NYCT DG 452A, *op. cit*.

Table 3-7 *Applicable Manuals and Guidelines for Structural Materials*

Document	Main Topic
American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary*, 2008	Reinforced and prestressed concrete
American Concrete Institute's *ACI-224R-01: Control of Cracking in Concrete Structures*, ACI Committee 224, 2002.	Concrete
Precast/Prestressed Concrete Institute's *PCI Design Handbook: Precast and Prestressed Concrete*.	Prestressed concrete
Smith, D. D. *Fiber Reinforced Concrete for Precast Tunnel Structures*. New York: Parson Brinckerhoff, Inc., 2011.	Fiber-reinforced concrete (FRC)
American Concrete Institute's *ACI 506.5R-09: Guide for Specifying Underground Shotcrete*, ACI Committee 506, 2009.	Shotcrete
AISC *Steel Construction Manual, 15th Edition*, 2017.	Steel structures
American Welding Society's Structural Welding Codes D1.1 and D.5, ASTM Standards	Steel structures
American Welding Society's *Structural Welding Code – Steel*, American National Standard Code AWSD1.1/D1.1.	Steel structures
ASCE-SEI Design of Wood Structures	Wood structures
American Society for Testing and Materials (ASTM)	Other
American National Standards Institute (ANSI)	Other

Waterproofing

Waterproofing must be designed to resist the anticipated hydrostatic pressures and negative effects of groundwater infiltration. There are two basic types of waterproofing systems: drained (open) and undrained (closed).

Open waterproofing systems (drained) allow groundwater inflow into a tunnel drainage system. The open system is commonly used in rock tunnels where water infiltration rates are low. The open waterproofing system generally allows for a more economical secondary lining and invert design, as the hydrostatic load is greatly reduced or eliminated.

Closed waterproofing systems (undrained), often referred to as tanked systems, extend around the entire tunnel perimeter and aim to exclude the groundwater from completely flowing into the tunnel drainage system. Thus, no groundwater drainage is provided and secondary linings must be designed for full hydrostatic water pressures. These systems are often applied in permeable soils where groundwater discharge into the tunnels would be significant.

Waterproofing systems may include:

- Water stops (treatment of penetrations)
- Gaskets
- Membrane waterproofing
- Liquid applied waterproofing

Permanent walls that do not have applied waterproofing, along with slurry walls, secant pile walls, and tangent pile walls used as the temporary support of excavation, should be subject to the permissible leakage criteria.

Permissible leakage criteria must be given in the contract specifications to determine the acceptability of the construction. The tunnel drainage system should be designed to accommodate the project leakage criteria. Criteria generally include a measured infiltration of volume/ft2/day and a maximum flow at any single point. Typical criteria range from 0.0002 to 0.01 gal/ft2/day, with 0.02 gal/minute of flow from any single leak. The owner must establish the required leakage criteria for long-term management of incoming water, the selected structural system and associated number of joints, and constituent components of the groundwater, including groundwater chemistry and contaminants. For immersed tunnels, no dripping or visible leakage from a single location will be permitted.

The allowable water infiltration values listed in Table 3-8 are based on criteria obtained from the International Tunneling and Underground Space Association (ITA), Singapore's Land Transport Authority, Singapore's Public Utilities Board, Hong Kong's Mass Transit Rail Corporation, and the German Cities Committee, as well as criteria used by various projects in the United States (e.g., Washington D.C., San Francisco, Atlanta, Boston, Baltimore, Buffalo) and others abroad (Melbourne, Australia, Tyne & Wear in the UK, and Antwerp, Belgium) for both highway and transit tunnels.

Table 3-8 *Allowable Infiltration*

Tunnels	≤ 0.002 gal/ft^2/day
Underground public space	≤ 0.001 gal/ft^2/day

The WMATA Standard Specifications (Section 7) allow for water leakage at rates of 0.08 to 0.14 gallons per 250 linear feet of tunnel, depending on the type of tunnel structure. Earlier tunnel designs did not incorporate a waterproofing membrane within the final tunnel liner construction nor in the station area. Significant water infiltration and corrosion were common problems with the previous design. WMATA adopted the new waterproofing method in 1983/1984 as part of a construction contract value engineering change proposal when it decided to utilize the SEM, also known as New Austrian Tunneling Method (NATM), for the Outer B Route.

Installation of this system begins with a smooth substrate layer of geotextile material attached to the tunnel crown and side walls by a steel nail and a PVC washer disk assembly. The geotextile material serves two functions: (1) to provide a drainage path for water infiltration that is directed to a collection system and (2) to provide a protection barrier between the initial liner surface and the waterproofing geomembrane. Once the geotextile material is securely fastened, the synthetic geomembrane (comprised of a PVC sheet material) is wrapped around the tunnel crown and sides and heat welded to the previously installed PVC washer disk assemblies. Membrane material is overlapped a minimum of 6 in (0.15 m), and the seams are heat welded.

At final cast-in-place liner construction joints and certain other locations, PVC water stop is attached to the membrane by heat welding. The water stop is used to define discrete liner segments (typically 50 ft long). After the waterproofing geomembrane has been installed, grout pipes are placed at specified locations prior to pouring the final concrete lining. The final concrete liner is then poured directly against the installed waterproofing system. If water intrusion later becomes a problem, these pipes can be accessed to inject a grout material that will seal the leak and provide an additional waterproof barrier.

The permanent concrete liner is protected from water intrusion by the geomembrane and the geotextile. The geomembrane acts as an impervious barrier and the geotextile serves to capture the water. The intercepted water flows to the bottom of the tunnel sides where it is transported by a special drain collection system. This water control system has resulted in significantly drier tunnel sections on the Outer B Route. More details about this system can be found in “Waterproofing and Its Effect on Operation and Maintenance of Underground Facilities,” FTA scope, March 1998.

Seismic Design

The tunnel structures should be designed to accommodate the deformations imposed by the ground. The structure must provide a high level of assurance for protection of life safety during and after a maximum design earthquake (MDE), or a safety evaluation earthquake (SEE). This earthquake produces the maximum level of ground motion for which a structure is to be designed or evaluated. The structure must also provide a high level of assurance of continued operation during and after a functionality evaluation earthquake (FEE).

- Determination of Seismic Environment
  - Earthquake fundamental
  - Ground motion hazard analysis
  - Ground motion parameters
- Factors That Influence Tunnel Seismic Performance
  - Seismic hazard
  - Geologic conditions
  - Tunnel design, construction, and condition

- Seismic Performance and Screening Guidelines of Tunnels
  - Screening guidelines applicable to all types of tunnels
  - Additional screening guidelines for bored tunnels
  - Additional screening guidelines for cut-and-cover tunnels
  - Additional screening guidelines for immersed tubes
- Seismic Evaluation Procedures – Ground Shaking Effects
  - Evaluation of transverse ovaling/racking response of tunnel structures
  - Evaluation of longitudinal response of tunnel structures
- Seismic Evaluation Procedures – Ground Failure Effects
  - Evaluation for fault rupture
  - Evaluation for land sliding or liquefaction

Applicable manuals and guidelines for seismic design are listed in Table 3-9 and supplementary documents are listed in Table 3-10.

Table 3-9 *Applicable Manuals and Guidelines for Seismic Design*

Document	Applicability
National Earthquake Hazard Reduction Program (NEHRP). NEHRP Requirements, latest version.	Direct application
AASHTO, *LRFD Road Tunnel Design and Construction Guide Specifications*.	Direct application
AASHTO, *LRFD Bridge Design Specifications*.	Supplementary information
AASHTO, *Guide Specifications for LRFD Seismic Bridge Design*.	Supplementary information
AREMA, *Manual for Railway Engineering*, Chapter 9 – Seismic Design for Railway Structures (Part 1.6.6 - Tunnels and Track Protecting Sheds).	General guidelines
LA Metro Rail Design Criteria Section 05.	General guidelines
Caltrans, Seismic Design Criteria Version 1.7 April 2013 (minimum seismic design requirements for bridges).	General guidelines
NYCT, Structural Design Guidelines, DG 452A.	General guidelines
Virginia State Building Codes and Regulations, VA-USBC 2009.	Supplementary information

Table 3-10 *Other Literature That Addresses Seismic Design*

Document	Applicability
Improved Seismic Design Criteria for California Bridges: Provisional Recommendations. Applied Technology Council, Report ATC-32, California Department of Transportation (Caltrans), 1996.	Supplementary information
Seyed-Mahan, M. *Procedures in Seismic Analysis and Design of Bridge Structures, release II draft*. Caltrans Division of Structures, California Department of Transportation, 1996.	Supplementary information
Idriss, I. M., and J. I. Sun, *User's Manual for SHAKE91: A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits*. Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California at Davis, 1992.	Supplementary information

Document	Applicability
Youd, T. L., and I. M. Idriss, eds. *Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils*. Technical Report NCEER-97-0022, National Center for Earthquake Engineering Research, 1997.	Supplementary information
Wang, J. *Seismic Design of Tunnels: A Simple, State-of-the-Art Design Approach*, William Barclay Parsons Fellowship, Parsons Brinckerhoff, Monograph 7, 1993.	Supplementary information
U.S. Department of Transportation, *Seismic Design Considerations for Mass Transit Facilities*, Publication No. DOT-T-94-19, 1994.	Supplementary information

Tunnel Construction

Railway tunnel construction incorporates the physical construction process of the tunnel. This section includes tunnel construction methodologies and relevant aspects for tunnel construction.

The common types of construction methods include cut-and-cover, shield driven, bored, jacked, immersed tube, drill and blast, and Sequential Evacuation Method (SEM). The tunnel's exterior shape usually changes with changes in the tunnel construction method or to accommodate greater stresses at depth. Some tunnels may have different shapes along their length because the ground conditions change along their length. For example, a tunnel could start out using shallow cut-and-cover techniques, but as it penetrates deeper into the subsurface and crosses under obstacles, other tunneling methods may be used, such as SEM, drill and blast, or even Tunnel Boring Machine (TBM) methods.

The construction methodology is dictated by:

- Ground condition
- Required clearance
- Economics
- Environment and available land around the portals
- Risk

Many rail tunnel construction aspects are similar to those typically used for road tunnel construction, so the material either overlaps or is similar. A notable exception is clearance, as that aspect is railroad specific. Another exception is tunnel finish, as the aesthetic of the tunnel finish is not as important for railroads as for roadways.

Tunnel Shape

The shape of railroad tunnels can vary and will depend on the depth, subsurface conditions, and surrounding structures. The existing literature does not specify or recommend tunnel shapes but lists the various types and typical situations in which each tunnel shape is used.[32]

There are three main shapes of highway tunnels—circular, rectangular, and horseshoe (or curvilinear). The shape of the tunnel is mainly dependent on the method used to construct it and on the ground conditions. For example, rectangular tunnels are often constructed by the cut-and-cover method, the immersed method, or jacked box tunneling. Circular tunnels are generally constructed using either TBM or drill and blast in rock. Horseshoe configuration tunnels are generally constructed using drill and blast in rock or SEM/NATM.

Tunnel Excavation Method

Many excavation methods are available for railroad tunnel construction. The excavation type used typically depends on depth, subsurface condition, surrounding structures, and cost. As with tunnel shape, the existing literature does not specify or recommend tunnel excavation methods but lists the various methods and typical situations in which each excavation method is used.

- Cut-and-cover tunnels (Figure 3-2) are built by excavating a trench, constructing the structure in the trench, and covering it with soil. The tunnels may be constructed in place or by using prefabricated sections.

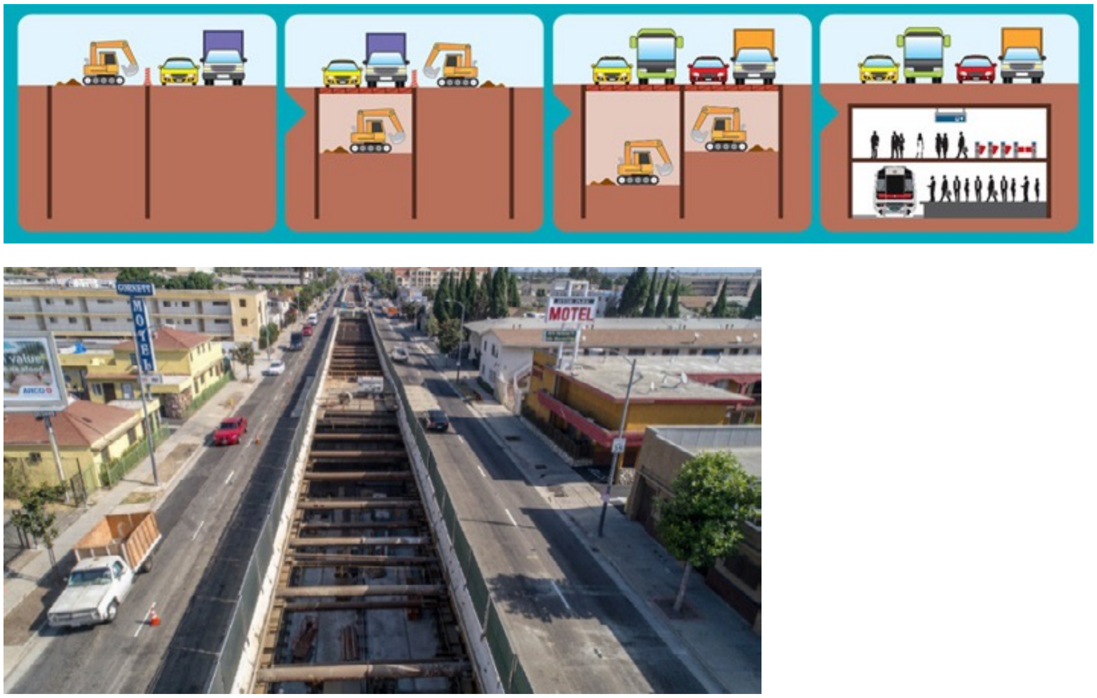
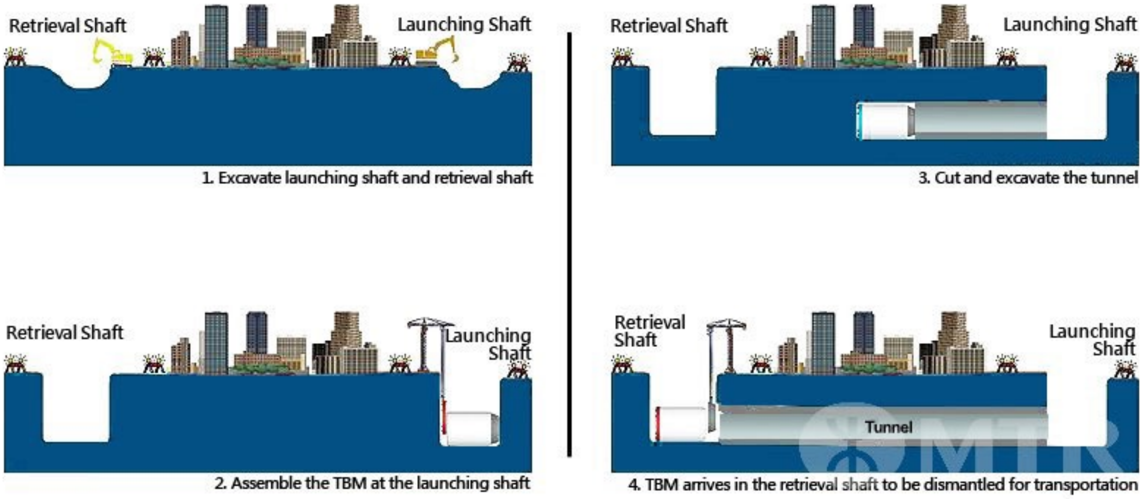


Figure 3-2 *Cut-and-cover tunneling method – Crenshaw/LAX line from above*

- Mined tunnels (Figure 3-3) are built utilizing mechanical excavating equipment or blasting without disturbing the ground surface. These tunnels are usually labeled according to the type of material being excavated.



1. Excavate launching shaft and retrieval shaft

2. Assemble the TBM at the launching shaft

3. Cut and excavate the tunnel

4. TBM arrives in the retrieval shaft to be dismantled for transportation

Figure 3-3 *Mined tunneling method*

- Bored tunnels are constructed using TBMs without disturbing the ground surface.
- Rock tunnels are excavated through the rock by drilling and blasting, by mechanized excavators in softer rock, or by using rock TBMs (Figure 3-4). In certain conditions, SEM is used.

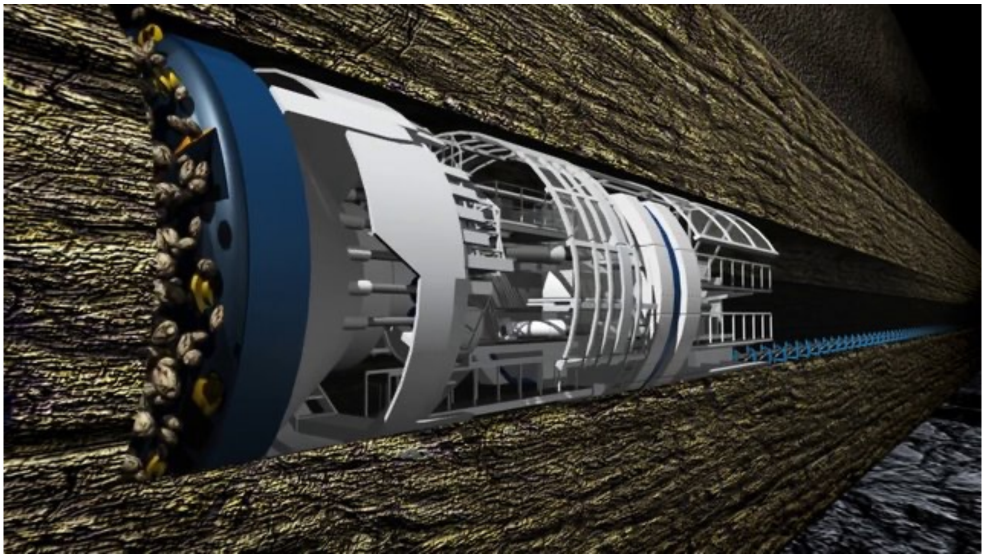


Figure 3-4 *Tunneling method using TBM*

- Soft ground tunnels are excavated in soil using a shield or pressurized face TBM (principally earth pressure balance or slurry types) or by mining methods known as SEM (Figure 3-5).

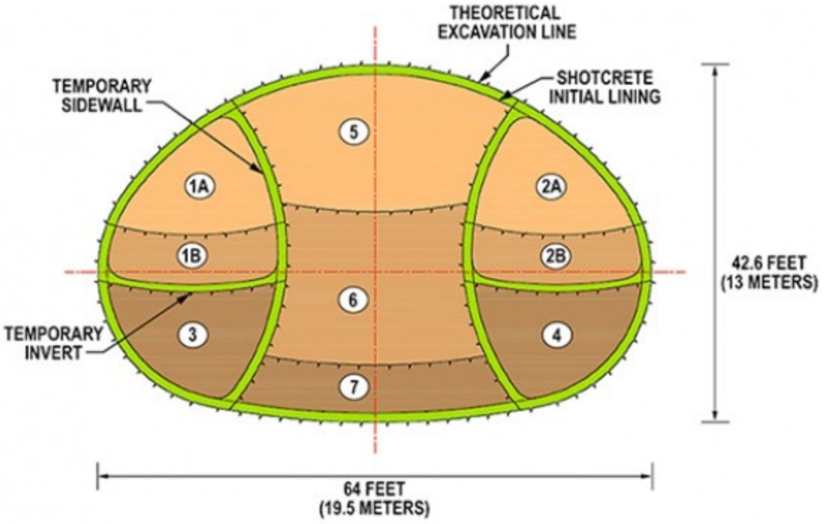


Figure 3-5 *Example of SEM*

- Immersed tunnels (Figure 3-6) are made from very large precast concrete or concrete-filled steel elements that are fabricated in the dry, floated to the site, placed in a prepared trench below water, connected to the previous elements, and then covered up with backfill.

Figure 3-6 *Example of immersed tunneling method – Fehmarn Tunnel construction*

- Jacked box tunnels (Figure 3-7) are prefabricated box structures jacked horizontally through the soil using methods to reduce surface friction. Jacked tunnels are often used for shallow depths where the surface must not be disturbed, such as beneath runways or railroad embankments. By using this method, flat tunnel structures can be built underneath existing infrastructure without affecting traffic on the surface.

Figure 3-7 *Example of jacked box tunneling method - Liberty University Tunnel, first jacked box tunnel in U.S.*

Initial Support Types

Tunnels excavated by TBM use precast concrete segmental linings. These linings may be either a one-pass precast concrete segmental lining or a two-pass precast concrete segmental lining with a cast-in-place concrete final lining. The open-type, or main beam, TBM does not install concrete segments. Instead, the rock is held up using ground support methods such as ring beams, rock bolts, shotcrete, steel straps, ring steel, and wire mesh.

Tunnels excavated by SEM use combinations of lattice girders, shotcrete, bolts, dowels, or self-drilling anchors (SDAs). Engineers have the option of designing different cast-in-place concrete or shotcrete final linings for defined reaches of the tunnel. Generally, the internal geometry of the tunnel remains constant, but lining thickness, reinforcement bar size, and spacing can be adjusted for different loading conditions.

Tunnels excavated using conventional mining methods, including SEM, use combinations of bolts, dowels, friction rock stabilizers, SDAs, steel ribs, lagging or lattice girders, and shotcrete. AASHTO LRFDs specify minimum length and maximum spacing for rock reinforcement,[33] gravity wedge analysis to determine anchor loads and orientation,[34] and reinforced roof arch.[35]

Tunnel Lining

Lining railway tunnels is important for maintaining the structural tunnel integrity and preventing the negative effects of groundwater infiltration.

Tunnel linings are structural systems installed after excavation to:

- provide ground support
- maintain the tunnel opening
- limit the flow of groundwater and/or gas
- support appurtenances
- provide a base for the final finished exposed surface of the tunnel

Tunnel linings are designed as compression members, considering the combined interaction of axial and moment load effect. Tunnel linings are designed for the second-order effects due to elastic deformations. Segmental linings are designed for the load effects resulting from construction tolerances.[36]

The selection of liner type will depend on multiple variables, including geotechnical material and quality, groundwater, costs, and aesthetics.

Much of the existing literature emphasizes liners:

- *AREMA Manual for Railway Engineering* Chapter 8, Part 11[37] – Covers cast-in-place concrete and shotcrete with steel sets
- LA Metro Rail – Cast-in-place concrete, precast segmental concrete, fabricated steel, and shotcrete[38]

SRT TSI[39] Section 2.4.1.2(a) states that the integrity of the tunnel lining must be maintained during a fire to allow for the safe evacuation of passengers. SRT TSI Section 2.4.1.2(b) states the same but for the tunnel's structure. More information about fire resistance of tunnel structures is presented in the Tunnel Supporting Systems section of this report.

Tunnels are often lined with concrete and internal finish surfaces. Some rock tunnels are unlined except at the portals and in certain areas where the rock is

---

[33] USACE (U.S Army Corps of Engineers), *Rock Reinforcement*, EM 1110-1-2907, Washington DC, February 1980.

[34] USACE, *Tunnels and Shafts in Rock*, EM 110-2-2901, Washington DC, May 1997.

[35] Bischoff, J. A., and J. D. Smart. "Method of Computing Rock Reinforcement System which is Structurally Equivalent to an Internal Support System," *Proceedings of the 16th Symposium of Rock Mechanics, University of Minnesota, Minneapolis*, September 22-24, 1975, 179-184.

[36] AASHTO LRFDTUN-1, *op. cit*.

[37] AREMA, *Manual for Railway Engineering*, Chapter 8, Part 11 – Lining Railway Tunnels, 2017.

[38] LA Metro Rail, *op. cit*.

less competent. In this case, rock reinforcement is often needed. The following types of linings are described in more detail in FHWA's technical manual for tunnels:[40]

- Cast-in-Place Concrete
- Precast Segmental Lining
- Steel Plate Lining
- Shotcrete Lining
- Selecting a Lining System

LA Metro Rail has established the general requirements and design procedures for tunnel linings utilizing FHWA's technical manual for tunnels,[41] Chapter 10 – Tunnel Lining, current edition, which incorporates LRFD.

The TOMIE Manual[42] recommends tunnel linings to have the following attributes: enhance visibility, be fire-resistant, not generate toxic fumes during fire, attenuate noise, and be easy to clean.

Refuge niches are another aspect that can be included in tunnel linings. In the *AREMA Manual for Railway Engineering*, refuge niches are described as openings within the tunnel lining that can be used to store equipment and people temporarily. Chapter 8, Part 11 (Section 8.11.27)[43] states that refuge niches should be placed at intervals of 200 ft (60 m) and staggered with opposite sides so the spacing of niches is approximately 100 ft (30 m) apart. The niche size should protect people and maintenance equipment. However, material should not be stored in refuge niches.

Ventilation during Construction

Proper ventilation of railway tunnels during tunnel construction or rehabilitation is necessary as improper ventilation can lead to severe physical injury and death for workers. A buildup of carbon monoxide, nitrogen dioxide, and other gases such as methane can be emitted from diesel engines. Gasoline engines are not permitted in tunnels due to gas and explosion risk.

Chapter 12, Part 4 of the *AREMA Manual*[44] specifies that hazardous materials arise as problems in two instances: design and construction. Hazardous soil materials must be properly identified, transported, and removed. Gases must

---

[39] EU 1303/2014, *op. cit*.
[40] FHWA-NHI-10-034, *op. cit*.
[41] *Ibid*.
[42] FHWA, *Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual*, Publication No. FHWA-HIF-15-005, July 2015.
[43] AREMA Manual 2017, Chapter 8, *op. cit*.
[44] *Ibid*, Chapter 12, Part 4.7 Rail Transit – Tunnels.

be detected using air quality detection systems and removed using ventilation techniques.

Chapter 1, Part 8 of the manual[45] has requirements for ventilation during construction or rehabilitation. These include:

- Airflow requirement of 100 cubic feet per minute (cfm) per total equipment diesel brake horsepower plus 200 cfm per person in tunnel.
- Linear air velocity requirement is 60 feet per minute.
- Carbon monoxide requirement is below 20 parts per million (ppm), nitrogen dioxide below 5 ppm, less than 20% for any flammable gas such as methane, and between 19.5 and 22% for oxygen.

More information about ventilation in emergencies is described in the following section.

Tunnel Supporting Systems

This section includes a summary of the topics contained within each regulation or standard. If multiple regulations or standards cover a topic, a brief comparison between the topics is made.

General Overview of Standards/Regulations

This overview covers three primary documents regarding the standards and regulations concerning fire and risk assessment in tunnels. The first two documents—NFPA 130 and NFPA 502—cover fire and other emergency standards for general fixed guideways and roadway tunnels. The third document—SRT TSI—includes transit tunnel regulations published by the European Union. Standards and regulations from individual European countries exist, but the general European code is used because of its extensiveness.

The NFPA 130[46] code focuses on passenger rail stations, trainways, and vehicles, emphasizing enclosed trainways, which would cover rail transit tunnels. The NFPA 502[47] code focuses on general highway locations with limited access, which would cover roadway tunnels. Both NFPA documents cover fire protection and fire and life safety requirements. The scope of the SRT TSI[48] includes preventing or mitigating the risks related to evacuation or rescue operations following a tunnel-specific railway incident. This means the codes have different scopes and focus on different topics. Specifically, the NFPA codes focus on fire prevention or mitigation, and the European SRT TSI codes focus on passenger evacuation. However, there are common sections in these codes and much overlap.

---

[45] *Ibid*, 2017, Chapter 1, *op. cit*.
[46] NFPA 130, *op. cit*.
[47] NFPA 502, *op. cit*.
[48] EU 1303/2014, *op. cit*.

An overview of the topics contained in the three documents is displayed in the following tables: Table 3-11 presents the infrastructure subsystem topics covered and Table 3-12 presents the energy subsystem topics.

Table 3-11 *Infrastructure Support System Topics Covered by Various Standards*

Topic	NFPA 130	NFPA 502	SRT TSI
Exits and Technical Rooms	6.3	-	4.2.1.1
Fire Resistance of Tunnel Structure	6.2	7.3	4.2.1.2
Fire Reaction of Building Materials	6.2	-	4.2.1.3
Fire Detection	6.4.4	7.4	4.2.1.4
Evacuation Facilities and Escape Walkways	6.3	7.16	4.2.1.5, 4.2.1.6
Fire Fighting Points	6.4.5	7.10	4.2.1.7
Emergency Communication and Train Control	10	7.5	4.2.1.8

Table 3-12 *Energy Support System Topics Covered by Various Standards*

Topic	NFPA 130	NFPA 502	SRT TSI
Segmentation of Overhead Line or Conductor Rails	-	-	4.2.2.1
Overhead Line or Conductor Rail Grounding	-	-	4.2.2.2
Electricity Supply	6.4.8	12.4	4.2.2.3
Electrical Cables	-	12.2 & 12.3	4.2.2.4
Reliability of Electrical Installations	-	12.5	4.2.2.5
Emergency Lighting	6.3.5	12.6	4.2.1.5

Chapter 12 of the AREMA Manual[49] is still in development, but it could eventually serve as a broad guideline for transit tunnel safety procedures and equipment. The following topics are anticipated to be covered: (1) train and car capacity, (2) crisis management, (3) fire, (4) loss of power, (5) train crash, (6) flooding, (7) emergency evacuation, (8) security (passenger safety and trespassers), (9) maintenance requirements (lighting, material storage, track capacity for maintenance, foot walk or other access for personnel), and (10) mechanical systems (HVAC, plumbing, maintenance access), utilities needed to support tunnel operations, and communication and train control. Many of these sections being developed will be relevant to tunnel supporting systems.

Infrastructure Support Systems

The infrastructure support systems section covers the necessary equipment and design for fire safety and passenger egress. All three documents cover the infrastructure support system extensively.

---

[49] *AREMA Manual* 2017, Chapter 12, *op. cit.*

Exits and Technical Rooms

Technical rooms are enclosed spaces with doors for access/egress inside or outside the tunnel with safety precaution installations, which are necessary for at least one of the following functions: self-rescue, evacuation, emergency communication, rescue and firefighting, signaling and communication equipment, and traction power equipment.

SRT TSI Section 4.2.1.1 states that unauthorized access should be prevented to technical rooms, and emergency exits should be locked from the outside but always allowed to open from the inside.[50] NFPA 130 and NFPA 502 do not cover this topic specifically, but the egress specifications in the documents are detailed in the next section.[51]

From discussions with transit agencies, an additional industry need is to ensure these exits self-close to reduce the escape of smoke or gases.

Evacuation Facilities and Escape Walkways

Evacuation facilities and escape walkways allow passengers, employees, and emergency responders to egress or access the area of a tunnel in which there is an incident. All three documents cover evacuation facilities and escape walkways. Evacuation facilities are also referred to as *safe areas*. NFPA 130 Section 6.3 states that exits should be located every 2,500 ft (762 m) with cross passages every 800 ft (244 m) if cross passages are used in lieu of emergency exit stairways. Other specifications are fire ratings of the exits, the inclusion of self-closing doors, and the size of escape walkways. NFPA 502 Section 7.16 states that exits should be located every 1,000 ft (300 m) and specifies signage, survivability timeframe, walking surfaces clearance and slippage, and emergency doors.

SRT TSI Section 4.2.1.5 states that safe areas should be located every 0.62 mi (1 km) and specifies size, length of survivable conditions, egress, door clearance, communication, lighting, and signage. SRT TSI Section 4.2.1.6 states that escape walkways should be of a certain size and have handrails.

Fire Resistance of Tunnel Structures

It is imperative to ensure the tunnel structure integrity remains after a fire to prevent a tunnel collapse. Both NFPA 502[52] and SRT TSI[53] cover fire resistance of tunnel structures. NFPA 502 Section 7.3 states the tunnel structure must withstand exposure by the Rijkswaterstaat (RWS) time-temperature curve or other recognized standard, meaning no permanent damage is allowed after

---

[50] EU 1303/2014, *op. cit*.
[51] NFPA 502, *op cit*.
[52] *Ibid*.
[53] EU 1303/2014, *op. cit*.

120 minutes. The fire curves are described in Appendix B of this report. SRT TSI Section 4.2.1.2 states that tunnel lining and surrounding structures must withstand temperatures of fire for sufficient periods. This period must be in accordance with evacuation scenarios included in the emergency plan. SRT TSI Section 2.4.1.2(a) states that the integrity of the tunnel lining should be maintained during a fire to allow for the safe evacuation of passengers. SRT TSI Section 2.4.1.2(b) states the same but for the tunnel structure.

The SRT TSI requirements are more general, in which the fire resistance should be determined based on location, type of traffic, and so on. The NFPA standards assume a tanker truck of 50 m3 of fuel with a fire load of 300 megawatts that lasts for 120 minutes, which is an assumption for road trucks and not necessarily applicable for railway vehicles. The SRT TSI guidelines suggest using the EUREKA curve (see Appendix B).

The International Tunneling Association's *Guidelines for Structural Fire Resistance for Road Tunnels* (May 2004) is another resource that covers guidelines for road tunnel structure fire resistance.

Fire Reaction of Building Materials

Ensuring the integrity of non-structural components is not necessary to avoid a collapse but to ensure that supporting systems keep working during a fire for safety reasons. Additionally, burning non-structural components can help fuel the fire and release toxic gases.

NFPA 130 Section 6.2 is dedicated to fire resistance and preventive measures during construction. This includes the use of standpipes during construction (6.2.1), types of material that can be used for each construction method (6.2.2), walkways (6.2.6), and multiple other railway components. NFPA 220, Standard on Types of Building Construction, is a common reference for fire resistance of construction materials.

NFPA 502 provides fire protection and life safety requirements for road tunnels, such as protection of structural elements, fire detection, communication systems, traffic control, fire protection, tunnel drainage system, emergency egress, and electrical and emergency response.

SRT TSI Section 4.2.1.3 states that construction products and building elements inside tunnels should comply with 2000/147/EC standards. These products include liners and all other non-structural products. NFPA 502 does not cover this topic.

Fire Detection

Fire detection systems are installed in tunnels to quickly communicate to the operations control center and emergency responders that a fire is present within a tunnel. All three documents cover fire detection. NFPA 130 Section 6.4.4 states that automatic heat and smoke detectors should be installed at traction power substations and signal bungalows. NFPA 502 Section 7.4 states manual and/or automatic alarms should be present depending on tunnel length and type. For tunnels with manual fire alarms, the alarms should be present every 300 ft (90 m) and at every cross-passage and means of egress. These alarms should be installed, inspected, and maintained in compliance with NFPA 72, National Fire Alarm and Signaling Code. Automatic fire detectors should be able to locate fire within 50 ft (15 m) and correspond to tunnel ventilation zones.

SRT TSI Section 4.2.1.4 states that fire detectors in technical rooms are required for tunnels longer than 0.62 mile (1 km) and that they should alert infrastructure managers in case of fire.

The International Fire Code (IFC)[54] provides minimum regulations for fire prevention and fire protection systems using prescriptive and performance-related provisions.

The National Cooperative Highway Research Program (NCHRP) Research Report 836[55] compiled a list of available fire detection and warning systems to detect smoke, gases, heat, and flames. NCHRP Report 836 recommends that detection system type selection should be based on the fire safety goals and overall fire safety strategy. The list includes:

- Linear (line-type) Heat Detection (LHD): These devices come in analog, digital, and fiber-optic versions. Recent tests show LHD devices can detect tunnel fires to a desired accuracy within 90 seconds by changes in semiconductor resistance (analog), component melting (digital), or light scattering (fiber optics). While these devices are proven to be long-lasting and reliable, they can be impacted by airflow, require replacement after a fire, and require long cables in long tunnel environments.
- CCTV (closed-circuit television) video image smoke detection: These devices detect fires by changes in brightness, contrast, edge content, loss of detail, and motion. Advantages include being able to be used for other purposes (security, smoke detection), covering large areas, tracking moving vehicles, and assisting emergency responders in better planning a response. Disadvantages include nuisance alarms, so multiple detections or confirmations are required before setting an alarm.
- Flame detectors: These devices sense fires by the amount of radiant energy they emit and include ultraviolet (UV), infrared (IR), ultraviolet-infrared (UVIR), or multiple wavelength IR systems. These systems have the advantage of working well in harsh environments; new systems have

---

[54] International Code Council (ICC), *International Fire Code* (IFC), 2015.

[55] Maevski, I., *Guidelines for Emergency Ventilation Smoke Control in Roadway Tunnels*, National Cooperative Highway Research Program, NCHRP Research Report 836, Transportation Research Board, 2017.

video cameras attached for visual confirmation and can detect fires within 60 seconds (the fastest based on current testing). Disadvantages include nuisance (false) alarms from welding, lightning, and so on, and a long detection range that allows a fire to be detected by multiple devices, making it difficult to determine the exact fire location.

- Spot-type heat detectors: These devices are more traditional and include many types such as duct smoke detectors, projected beam-type smoke detectors, and heat detectors. Advantages include being readily available, not requiring specialized contractors, and being inexpensive. Disadvantages include difficulties with reducing nuisance alarms to detect fires quickly.

Using two or more alarm systems enhances fire detection capabilities and tunnel fire safety. Care should be taken when using automatic devices, as conditions can rapidly change.

Fire Fighting Points

For longer tunnels, typical firefighting equipment cannot access the tunnel; therefore, built-in firefighting points, also referred to as standpipes, are necessary to combat fires. All three documents address firefighting points. NFPA 130 Section 6.4.5 requires standpipe and hose systems every 800 ft (244 m), fed from two locations, identifiable, and able to supply at least one hour of water. NFPA 502 Section 7.10 states that firefighting points are mandatory in Type C (1,000–3,280 ft; 305–1,000 m) and D (>3,280 ft; > 1,000 m) tunnels and should be part of an integrated system. Specifics will vary on the tunnel type. Additionally, the firefighting point should be capable of supplying water at the necessary capacity for a minimum of an hour. Hose connection types should be communicated to the local fire departments.

SRT TSI Section 4.2.7 states the number of firefighting points be determined based on the tunnel length and type of rolling stock. These firefighting points should be equipped with sufficient water supply and accessible to emergency response units.

Emergency Communication and Train Control

During an incident, communication between the railway crew, passengers, or emergency responders with the operations control center is important for coordination and efficient response. Both NFPA 502 and SRT TSI cover emergency communication. NFPA 130 Section 10.4 and NFPA 502 Section 7.5 state that two-way radio systems should be installed in tunnels. SRT TSI Section 4.2.8 states that emergency communication be located in tunnels over 0.62 mi (1 km) and ensure fixed and mobile communication in safe areas.

Train control technologies are important for reducing the number of incidents within tunnels. Chapter 12 Section 4.7.3.12 of the *AREMA Manual* mentions coordinating signals between equipment rooms, trackside equipment, and emergency communications. In addition, there should be an equipment room with emergency communication capabilities and emergency telephones along escape walkways.

Energy Support Systems

Energy support systems cover the necessary equipment to supply electrical power to the tunnel. This topic is addressed by both NFPA 502 and SRT TSI; however, SRT TSI has additional topics that are solely related to train transit. NFPA 130 only addresses emergency lighting and does not have a section on energy support systems.

Energy Segmentation of Overhead Line or Conductor Rails

SRT TSI Section 4.2.2.1 states that traction energy supply should be divided into sections not exceeding 3.1 mi (5 km) if the signaling system allows for the presence of more than one train. NFPA 502 emphasizes motor vehicle road tunnels and does not cover energy segmentation.

Overhead Line or Conductor Rail Grounding

SRT TSI Section 4.2.2.2 states that grounding devices should be provided at tunnel access points. Groundings can be portable or fixed installations that are manually or remotely controlled. NFPA 502 emphasis is on motor vehicle road tunnels.

Electricity Supply

Keeping a backup electricity supply is imperative to ensure supporting systems have the power to function as intended during emergencies if the primary power source shuts down. NFPA 130 Section 6.4.8 and NFPA 502 Section 12.4 state that emergency power must be in accordance with Article 700 of NFPA 70.[56] NFPA 130 states that emergency lighting, protective signaling systems, emergency communication systems, and the fire command center should be covered. NFPA 502 states that emergency power should cover the following: emergency lighting, tunnel closure and traffic, exit signs, emergency communication, tunnel drainage, emergency ventilation, fire alarm and detection, closed-circuit television (CCTV) or video, and firefighting. SRT TSI Section 4.2.2.3 states that the electricity supply should be sufficient for emergency response.

---

[56] NFPA, *NFPA 70: National Electrical Code* (NEC), 2017.

Electrical Cables

As with the electricity supply, ensuring the electric cables are protected and working during an emergency is imperative to maintaining power for support systems to function as intended. NFPA 502 Section 12.2 states that all cable and conductors should be moisture resistant and heat resistant with temperature ratings that correspond to the conditions of application. Additionally, all wiring should be listed as fire-resistant and low smoke-producing. NFPA 502 Section 12.3 states that cables and conductors should be protected through metallic armor/sheath, metal raceways, electric duct banks embedded in concrete, or other approved methods. The cabling in certain locations, such as supply air ducts, should have fire-resistant and low smoke-producing characteristics. SRT TSI Section 4.2.2.4 states that all exposed cables must have low flammability, low fire spread, low toxicity, and low smoke density characteristics.

Reliability of Electric Installations

Ensuring the electrical installations remain working during an emergency is also important for the supporting systems to function as intended. NFPA 502 Section 12.5 states that electrical systems of tunnels exceeding 0.62 mi (1 km) should have redundant facilities for monitoring and control. SRT TSI Section 4.2.2.5 states that electrical installations for safety should be protected against damage arising from mechanical impact, heat, or fire. Additionally, these installations must have an alternative power supply after failure of main power supply for a length determined in emergency response plans.

Emergency Lighting

Tunnel lighting during an emergency is needed for passenger egress. NFPA 130 Section 6.3.5 states that the illumination of emergency walkways should be 2.7 lx or greater, and exit lights, essential signs, and emergency lights should be in accordance with NFPA 70. NFPA 502 Section 12.6 states that electrical systems should be in accordance with NFPA 70,[57] NFPA 110,[58] and NFPA 111[59] and that emergency lights, exit lights, and essential signs should be included in the emergency lighting system and powered by an emergency power supply. Additional standards include wiring, no greater than 0.5 seconds of light interruption, illumination levels between 1 and 10 lx, and maximum-to-minimum illumination ratios of 40 or less. SRT TSI Section 4.2.1.5 states that for tunnels greater than 0.31 mi (0.5 km), emergency lighting must guide passengers and staff to a safe area and have an alternative power supply. Additional topics include lighting location, the position of lights, and illuminance of at least 1 lx.

---

[57] ibid.

[58] NFPA 110: Standard for Emergency and Standby Power Systems, 2010.

[59] NFPA 111: Standard on Stored Electrical Energy Emergency and Standby Power Systems, 2016.

Other relevant documents for lighting and emergency lighting are ANSI/IEEE-ANSI C2,[60] ANSI/IES RP-22,[61] CIE 88:2004,[62] and CIE 193:2010.[63] Two documents by the Illuminating Engineering Society include:

- IES LM-50 – Lighting Measurements–50 provides a uniform test procedure for determining, measuring, and reporting the luminance characteristics of roadway lighting installations.
- IES RP-22 – Recommended Practices–22 provides information to assist engineers and designers in determining lighting needs, recommending solutions, and evaluating resulting visibility at vehicular tunnel approaches and interiors.

Electrical Safety

The following codes are relevant to electrical safety:

- NETA MTS-2011 – The International Electrical Testing Association (NETA), Maintenance Testing Specifications were developed for those responsible for the continued operation of existing electrical systems and equipment to guide them in specifying and performing the necessary tests to ensure these systems and apparatuses perform satisfactorily, minimizing downtime and maximizing life expectancy.
- NFPA 70 – National Fire Protection Association 70 covers installing electric conductors and equipment within or on public and private buildings or other structures; conductors and equipment that connect to the electricity supply; other outside conductors and equipment on the premises; and optical fiber cables and raceways.
- NFPA 70B – National Fire Protection Association 70B is recommended practice for electrical equipment maintenance for industrial-type electrical systems and equipment but does not intend to duplicate or supersede instructions that electrical manufacturers normally provide.
- NFPA 70E – National Fire Protection Association 70E addresses employee workplace electrical safety requirements necessary for the practical safeguarding of employees.

Ventilation

During an incident that releases heat, smoke, or other toxic emissions, a ventilation system is necessary to provide a non-contaminated environment for passenger evacuation and to facilitate firefighting and rescue operations.

---

[60] IEEE (Institute of Electrical and Electronics Engineers), IEEE-ANSI C2-2017, National Electric Code Lighting, 2017.

[61] IES (Illuminating Engineering Society), ANSI/IES- RP-22, Standard Practice for Tunnel Lighting, 2011.

[62] CIE (Commission Internationale de L'Eclairage), *Guide for the Lighting of Road Tunnels and Underpasses*, Technical Report CIE 88:2004, 2004.

[63] CIE, *Emergency Lighting in Road Tunnels*, Technical Report CIE 193:2010, 2010.

There are multiple types of ventilation systems that have specific benefits and downsides, depending on the tunnel characteristics. This section discusses ventilation during emergencies; ventilation in non-emergency situations is discussed in the Tunnel Construction section of this report.

The authors are unaware of standards for tunnel ventilation during transit tunnel operations because natural ventilation from the piston effect of the passing train is generally considered sufficient for electrically powered vehicles (third rail). Tunnels with operations of diesel-powered vehicles may require different ventilation needs. Ventilation may also be used during inspection and maintenance on an as-needed basis.

NFPA 130 and NFPA 502[64] cover emergency ventilation requirements for road tunnels and can be supplemented by NCHRP Report 836,[65] which states that the best practices mentioned do not apply to railway tunnels. However, both the NFPA 130 and NCHRP 836 documents can serve as a foundation for what is required for railway tunnels. The authors are unaware of European standards, as SRT TSI does not cover emergency ventilation.

There are three major forms of railroad tunnel ventilation: (1) piston effect with an open-ended tunnel, (2) piston effect with a portal gate, and (3) mechanical ventilation with a portal gate (AREMA). TOMIE[66] suggests five main types of ventilation: natural, longitudinal, semi-transverse, full-transverse, and single-point.

The AASHTO recommendations state that longitudinal ventilation and extraction ventilation are commonly used for roadway tunnels. The ventilation type to use will depend on the individual tunnel characteristics, such as tunnel length, type of traffic, unidirectional or bidirectional traffic, and so on.

The longitudinal ventilation concept directs smoke inside the tunnel in the opposite direction of egress by completely pushing the smoke to one side of the fire (preferably applied to non-congested unidirectional tunnels). It introduces air into or removes smoke and gases from the tunnel at a limited number of points, primarily by creating longitudinal airflow through the length of the tunnel from one portal to another. This can be accomplished by injection, central fans, jet fans, nozzles, or some combination. The system must generate sufficient longitudinal air velocity, called critical velocity, to prevent backlayering of smoke. A diagram of longitudinal venting is illustrated in Figure 3-8 and a diagram of backlayering is displayed in Figure 3-9. NFPA 502 states that longitudinal systems must (a) prevent backlayering by producing a longitudinal air velocity that is calculated based on critical velocity in the

---

[64] NFPA 502, *op. cit*.

[65] NCHRP Report 836, *op. cit*.

[66] FHWA-HIF-15-005, *op. cit*.

direction of traffic flow, and (b) avoid disruption of the smoke layer initially by not operating fans that are located near the fire site, and operating fans farthest from the site first.

Figure 3-8 *Longitudinal ventilation controlling smoke and hot gases (AASHTO 2016)*

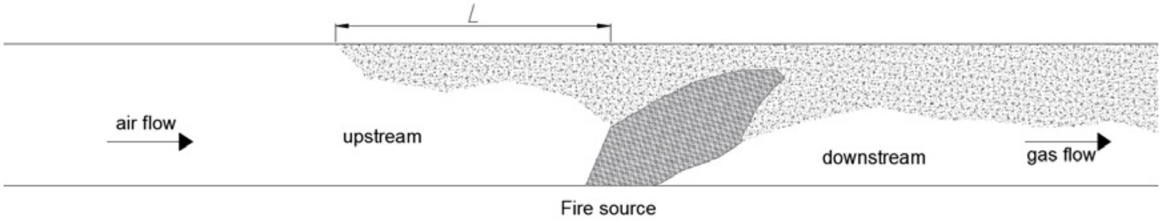


Figure 3-9 *Backlayering of smoke in tunnel where backlayer length is L (modified from AASHTO 2016)*

The extraction ventilation concept extracts smoke at the fire location by keeping the smoke stratification intact, leaving relatively clean and breathable air suitable for evacuation underneath the smoke layer to both sides of the fire (applicable to bidirectional or congested unidirectional tunnels and is typically achieved by zoned transverse ventilation or single point extraction). Extraction ventilation typically requires exhaust ventilation ducts and a system capable of localizing hot gases and smoke and extracting them at the fire location using exhaust fans rated for high temperatures.

A diagram of transverse extractive venting is illustrated in Figure 3-10. NFPA 502[67] states transverse or reversible semi-transverse systems must (a) maximize the exhaust rate in the ventilation zone that contains the fire and minimize the amount of outside air introduced by a transverse system, and (b) create a longitudinal airflow in the direction of traffic flow by operating the upstream ventilation zones in maximum supply and the downstream ventilation zones in the maximum exhaust.

---

[67] NFPA 502, *op. cit.*

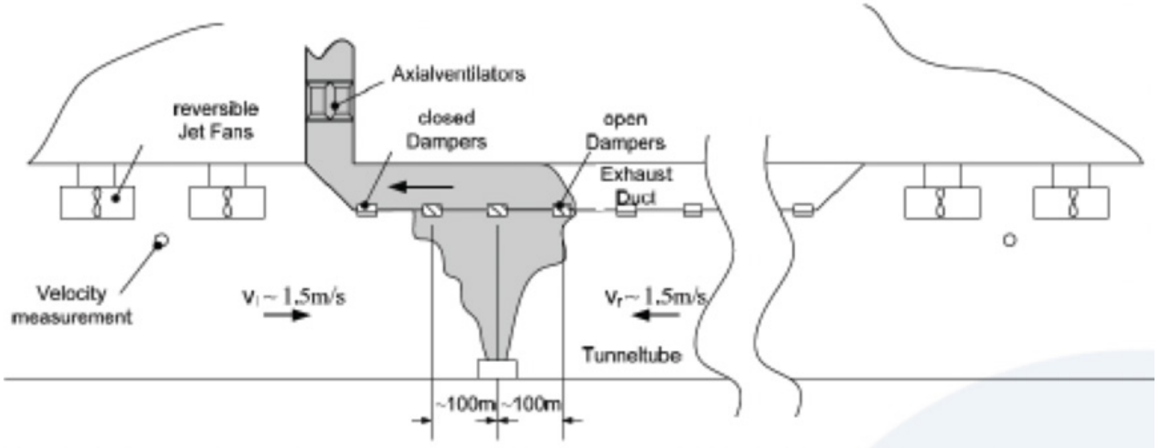


Figure 3-10 *Extractive ventilation controlling smoke and hot gases (AASHTO 2016)*

NFPA 130 states that mechanical emergency ventilation systems should be provided for an underground or enclosed trainway that is greater than 1,000 ft (305 m). The design objectives of the emergency ventilation system are to (1) provide a tenable environment along the path of egress from a fire incident in enclosed trainways, (2) produce sufficient airflow rates within enclosed trainways to meet a critical velocity, (3) be capable of reaching full operational mode within 180 seconds, (4) accommodate the maximum number of trains that could be between ventilation shafts during an emergency, and (5) maintain the required airflow rates for a minimum of one hour but not less than the required time of tenability.

The design also should incorporate fire scenarios and fire profiles; station and trainway geometries; the effects of elevation, elevation differences, ambient temperature differences and ambient wind; a system of fans, shafts, and devices for directing airflow in stations and trainways; a program of predetermined emergency response procedures capable of initiating prompt response from the operations control center during a fire emergency; and a ventilation system reliability analysis that, as a minimum, considers electrical, mechanical, and supervisory control subsystems.

NFPA 502 states the design objectives of an emergency ventilation system should be to control and extract smoke and heated gases as follows: (1) a stream of non-contaminated air is provided to motorists in paths(s) of egress in accordance with the anticipated emergency response plan, and (2) longitudinal airflow rates are produced to prevent backlayering of smoke in a path of egress away from a fire. The design should consider heat release rates, smoke release rates, and carbon monoxide release rates, all varying with a function of time. The operational risks associated with the type of vehicles expected to use the tunnel should also be considered.

Requirements of NFPA 502 include but are not limited to:

- Tunnel length that emergency ventilation is required
- Ventilation systems should be sized to meet requirements with one fan out of service
- Standards for smoke control, fans, dampers, sound attenuators, and controls

Chapter 12 Part 4 of the *AREMA Manual*[68] states that fire is considered the worst type of crisis because the confined nature of a tunnel can trap passengers, heat, and gases. Underground transit tunnels must provide ventilation plants for bidirectional air movement and meet required flow characteristics. These plants must communicate so they can blow smoke in the opposite direction of the evacuation route. Fire mains and access for firefighters must be incorporated into the design.

Other documents relevant to emergency ventilation include the National Cooperative Highway Research Program (NCHRP) Synthesis 415,[69] *Design Fires in Road Tunnels*, and the World Road Association (PIARC) *Integrated Approach to Road Tunnel Safety*.[70]

Supplementary information can be found in NFPA 92B,[71] Standard for Smoke Management Systems in Malls, Atria, and Large Spaces, and Air Movement and Control Association's *Fan and Air System Applications Handbook*.[72]

In addition to emergency ventilation, proper ventilation of railway tunnels during construction and service is important, as improper ventilation can lead to severe physical injury and death for workers or stranded passengers during a train malfunction. Train use can lead to the accumulation of exhaust gases and heat in long tunnels. Additionally, excessive heat can cause the locomotive to cease to function.

Nitrogen dioxide is the prominent air contaminant from diesel locomotive engines. This gas tends to rise and accumulate at the top of the tunnel, above the train and any walking persons. However, a significant portion will remain in the lower part of the tunnel.

Chapter 1 Part 8 Section 1.8.7.1 of the *AREMA Manual* lists the following thresholds for air contaminants:

---

[68] *AREMA Manual* 2017, Chapter 12, *op. cit*.

[69] Maevski, I. *Design Fires in Road Tunnels*. National Cooperative Highway Research Program, NCHRP Synthesis 415, Transportation Research Board, 2011.

[70] World Road Association-PIARC, *Integrated Approach to Road Tunnel Safety R07*, 2007.

[71] NFPA 92B: Standard for Smoke Management Systems in Malls, Atria, and Large Spaces, 2015.

[72] AMCA (Air Movement and Control Association International), *AMCA Fan and Air System Applications Handbook*, June 2012.

- Airflow of 100 cubic ft per minute (cfm) per total equipment diesel brake horsepower plus 200 cfm per person in tunnel.
- Minimum linear airflow velocity is 60 ft/minute.
- Air quality alarms should be set if the following requirements are exceeded: 20 parts per million (ppm) for carbon monoxide, 5 ppm for nitrogen dioxide, 20% for methane or other flammable liquid, and an oxygen level below 19.5% or above 22%.

Section 1.8.7.2 of Chapter 1 Part 8 adds that there should be a ventilation system for long tunnels.

Fixed Fire Fighting Systems

While not required by NFPA 130, NFPA 502, or SRT TSI, fixed firefighting systems (FFFS) are available for tunnels. The purpose of these systems is to slow, stop, or reverse the fire growth rate or otherwise mitigate the impact of fires (NFPA 502). However, there are advantages and disadvantages of FFFS, and all factors should be considered before installation and implementation. It is noted that the efficiency of water-based FFFS depends on the size and type of fire, nozzle type, sprinkler location, and water discharge rate.

Some advantages of FFFS are protecting tunnel users and structure and supporting rescue and firefighting in the early stages of a fire. Some disadvantages include reduced visibility, destruction of smoke stratification, a slippery environment, and possible reduction in ventilation effectiveness. Due to the interaction between ventilation and FFFS, the two systems should be coordinated to prevent reduced effectiveness of both systems during a fire. Two types of water-based FFFS systems per NCHRP Report 836[73] include:

- Deluge sprinklers – These devices are essentially sprinkler heads that suppress fires mainly by surface cooling.
- Water mist – These devices spray a mist that suppresses fires by dilution and gas cooling.

Fusible link or high expansion foam sprinkler systems are also available but less common.

Drainage

Drainage should be considered during all phases of the tunnel life span to prevent the negative effects of groundwater. In case of toxic or flammable materials spills, proper drainage prevents the material from spreading.

NFPA 130 does not mention drainage. NFPA 520 states that a tunnel drainage system should be provided to collect, store, or discharge effluent from the

---

[73] NCHRP Report 836, *op. cit*.

tunnel, or to perform a combination of these functions. This includes designing a drainage collection system to capture and minimize the spread of liquids. In addition, the drainage system should have the capacity to prevent flooding.

Chapter 8 of the *AREMA Manual*[74] states that vertical and diagonal openings, trench drains, PVC, or iron pipe drains should be installed between the concrete lining and rock whenever groundwater is encountered to port water away from the tunnel structure. This drainage should consider groundwater constituents to discourage the formation of precipitates or adverse chemical reactions that may plug or damage the drainage system.

Track Structure Safety Standards

The Federal Railroad Administration (FRA) has general track safety standards in 49 CFR 213[75] and railroad bridge-specific standards with the *Track and Rail and Infrastructure Integrity Compliance Manual*.[76] However, no FRA document has specific regulations for tunnels.

Rolling Stock Systems

The rolling stock is important for tunnel safety because the greater risk of a rolling stock catching fire and emitting toxic gases, the more dangerous tunnel fires can be for passengers, employees, emergency responders, and the tunnel structure itself. The scope of this report does not detail the regulations and standards for rolling stock. However, rolling stock standards exist, including the European Union's Rolling Stock - Locomotives and Passengers TSI[77] and U.S. standards provided in NFPA 130.[78]

Technologies to Aid Supporting Systems

The continuous advancement in technology and computing power allows new solutions to aid supporting systems.

Flooding

The flooding of the New York City subway system during Hurricane Sandy resulted in damages upward of $10 billion. As a result, new technologies to mitigate flooding damage have been proposed and tested. While hurricanes and storms represent the primary motivation, flooding from other sources such as dam breaks also apply.

---

[74] *AREMA Manual*, 2017, Chapter 8, *op. cit*.

[75] FRA, Code of Federal Regulations, Part 213 – Track Safety Standards. 49 CFR 213, October 2011.

[76] FRA, *Track and Rail and Infrastructure Integrity Compliance Manual*, Volume IV, Chapter 1, Bridge Safety Standards, January 2015.

[77] EU 1302/2014, *op. cit*.

[78] NFPA 130, *op. cit*.

The difficulty in stopping floodwater in subway tunnels is ensuring all the entrances—portals, ventilation shafts, emergency exits, stairwells, elevator shafts, man covers, and son on—are appropriately sealed with a system that can be stored on site using minimal storage volume, deployed quickly, stored again after use, and that provides the required reliability to maintain flooding protection during the entire duration of the storm or event.

One technology currently being tested during the assembly of this report is a Resilient Tunnel Plug (RTP) developed by ILC Dover, working with the Department of Homeland Security Science and Technology Directorate, Department of Energy's Pacific Northwest National Laboratory, and West Virginia University. The Plug is essentially a resilient balloon stored near the track that rapidly inflates to plug the tunnel when activated (Figure 3-11). While the RTP was originally designed for subway floods, it could also be used to mitigate against the spread of smoke, fire, and chemical/biological agents. Spinoff technologies from the RTP, which uses high-strength Vectran® fabric, involve gates, walls, and covers for stairwells, portals, and other entrances.

Figure 3-11 *Photograph of the RTP (DHS 2014)*

The current solution of flood gates, when employed, creates a water-tight barrier that seals the entire portal to the tunnels. The full closing operation may take approximately 30 minutes; therefore, the portable systems could be a good quick backup.

Video Surveillance

Video surveillance can play many roles in tunnel security by detecting and identifying trespassers, smoke, and fires. Advances in CCTV and video analytics allow specialized detection systems to optimize security. These can include object detection and classification, which allows the video analytic software to differentiate between trains, animals, and human trespassers, determine direction flow, and count people to help aid emergency response.

Multiple companies provide video analytic systems. To date, the authors are unaware of any best practices for these types of systems that can be used for transit tunnels.

Tunnel Security and Risk Assessment

This literature review section presents various standards, guidelines, and regulations regarding tunnel security and risk along with tunnel support systems. These two areas are combined because tunnel supporting systems are typically required for security and risk reasons. This section offers a general overview of existing standards and guidelines, detailed descriptions of the topics addressed by each standard and/or guideline, and some other notable aspects of tunnel security and risk.

Safety Operations and Emergency Response

In 2005, FHWA, AASHTO, and NCHRP sponsored a scanning study of equipment, systems, and procedures used in European tunnels. The study concluded with nine recommendations for implementation. These recommendations encompassed conducting research on tunnel emergency management that includes human factors; developing tunnel design criteria that promote optimal driver performance during incidents; developing more effective visual, audible, and tactile signs for escape routes; and using a risk-management approach to tunnel safety inspection and maintenance. The study's nine recommendations are listed below:[79]

- Develop universal, consistent, and more effective visual, audible, and tactile signs for escape routes.
- Develop AASHTO guidelines for existing and new tunnels.
- Conduct research and develop guidelines on tunnel emergency management that includes human factors.
- Develop education for motorist response to tunnel incidents.

---

[79] International Technology Scanning Program, *Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response*, Report No. FHWA-PL-06-016, June 2006. https://international.fhwa.dot.gov/uts/uts.pdf.

- Evaluate effectiveness of automatic incident detection systems and intelligent video for tunnels.
- Develop tunnel facility design criteria to promote optimal driver performance and response to incidents.
- Investigate one-button systems to initiate emergency response and automated sensor systems to determine response.
- Use risk-management approach to tunnel safety inspection and maintenance.
- Implement light-emitting diode lighting for safe vehicle distance and edge delineation in tunnels.

Security

Tunnels present themselves as threat targets for a wide range of antisocial activities for various reasons. These reasons can range from vandalism and trespassing to terrorist attacks because some tunnels represent a chokepoint in a transportation system.

Risk analysis and management are essential for any underground project. Major risk categories include construction failures, public impact, schedule delay, environmental commitments, failure of the intended operation and maintenance, technological challenges, unforeseen geotechnical conditions, and cost escalation.

It its Recommended Practice for tunnel security, APTA (2015) lists the following potential threats:[80]

- Explosive
- Chemical, biological, or radiological (CBR)
- Improvised incendiary device (IID), fire, arson
- Sabotage
- Cyber attack
- Maritime accident

Table 3-13 and Table 3-14 list threats and the associated consequences produced inside a tunnel structure. The tables also list potential mitigation techniques for each threat (from APTA 2015).

---

[80] APTA, *Tunnel Security for Public Transit*, APTA Standards Development Program Recommended Practice APTA SS-SIS-RP-16-15, Washington, DC, March 2015.

Table 3-13 *Potential Consequences from Each Tunnel Threat (APTA 2015)*

Threats	Fire/ Smoke	Flooding	Structural Integrity Loss	Contamination	Utility Disruption	Extended Loss of Use	Extended Public Health Issues
Explosive (small, large)	✓	✓	✓	✓	✓	✓	✓
CBR				✓		✓	✓
IID, Fire, Arson	✓	✓	✓	✓	✓	✓	✓
Sabotage	✓	✓	✓	✓	✓	✓	✓
Cyber					✓	✓	
Maritime Incident		✓	✓			✓	

Table 3-14 *Matrix of Threats and Mitigations (APTA 2015)*

Mitigation Measure	Threats					
	Explosives	CBR	IID Fire/ Arson	Sabotage	Cyber	Maritime Incident
Access control systems	✓	✓	✓	✓		
Anti-vehicle barriers	✓	✓	✓	✓		
Barriers and fencing	✓	✓	✓	✓		✓
Clear zones	✓	✓	✓	✓		✓
Crime prevention through environmental design	✓	✓	✓	✓		✓
Designated zones	✓	✓	✓	✓		✓
Electronic security systems	✓	✓	✓	✓		
Emergency egress	✓	✓	✓	✓		✓
Entry control	✓	✓	✓	✓		
Fire detection systems	✓	✓	✓	✓		
Fire suppression systems	✓	✓	✓	✓		
Intrusion detection systems	✓	✓	✓	✓		
Layered protection	✓	✓	✓	✓	✓	✓
Security patrols	✓	✓	✓	✓		✓
Security and emergency response policies and procedures	✓	✓	✓	✓	✓	✓
Security and emergency lighting	✓	✓	✓	✓		
Sensitive security information	✓	✓	✓	✓	✓	✓
Signage	✓	✓	✓	✓		✓
Standoff distance	✓	✓	✓	✓		✓
Video surveillance systems	✓	✓	✓	✓		✓
Walkways	✓	✓	✓	✓		✓

In addition, APTA (2015) recommends an integrated security system, a coordinated security plan with relevant agencies, and security training exercises.

Other documents that have recommendations on tunnel security are the *AREMA Manual for Railway Engineering* (Chapter 12.4) and SRT TSI.

Some tunnel security designs include emergency call stations (ECS), global positioning systems (GPS), automated vehicle locator (AVL), positive train control (PTC), and supervisory control and data acquisition (SCADA).

Chapter 12.4 of the *AREMA Manual* treats security differently from safety, as security involves preventing undesired access or undesired acts by individuals with antisocial intent. Mitigations typically involve locks, alarms, and making access difficult.

Two additional sources include:

- FHWA – Recommendations for Bridge and Tunnel Security, Blue-Ribbon Panel on Bridge and Tunnel Security, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, April 1999.
- Transit Cooperative Research Program and National Cooperative Highway Research Program – Making Transportation Tunnels Safe and Secure, TCRP Report 86/NCHRP Report 525, Vol. 12,Transportation Research Board, Washington, DC, November 2006.

Emergency Response Plan

Developing emergency response plans and practicing emergency response are imperative for reducing the risks of emergency situations in tunnels. Multiple incidents can occur in tunnels; thus, agencies responsible for operations should have emergency response plans for the following incident types, if applicable (NFPA 130, 2017):

- Fire or smoke conditions within the system structures, including stations, guideways, and support facilities
- Collision or derailment involving rail vehicles on the guideway, rail vehicles with privately owned vehicles, intrusion into the right-of-way from adjacent roads or properties
- Loss of primary power source resulting in stalled trains, loss of illumination, and availability of emergency power
- Evacuation of passengers from a train to all right-of-way configurations under circumstances where assistance is required
- Passenger panic

- Disabled, stalled, or stopped trains due to adverse personnel/passenger emergency conditions
- Tunnel flooding from internal or external sources
- Disruption of service due to disasters or dangerous conditions adjacent to the system, such as hazardous spills on adjacent roads or police activities or pursuits dangerously close to the operational systems
- Hazardous materials accidentally or intentionally released into the system
- Serious vandalism or criminal acts, including terrorism
- First aid or medical care for passengers on trains or in stations
- Extreme weather conditions, such as heavy snow, high or low temperatures, sleet, or ice
- Earthquakes
- Any other emergency as determined by the authority having jurisdiction

Due to the complex nature of emergencies and the multiple agencies that must participate, many agencies must participate and coordinate in developing or approving emergency response plans. These agencies include the following (NFPA 130, 2017):

- Ambulance services
- Building department
- Fire department
- Medical service
- Police department
- Public works
- Sanitation department
- Utility companies
- Water supply
- Local transportation companies
- Red Cross, Salvation Army, and similar agencies

NFPA 130 covers minimum requirements for emergency response plans, including a list of emergency incidents to be prepared for, the scope of the emergency response plan, a list of participating agencies, and training. In addition, it lists requirements for the operations control center, including but not limited to proper qualification and training; the ability to directly communicate with all the participating agencies and record all conversations; and protection from fire and attacks. NFPA 502 covers similar topics, but additional references and standards are in NFPA 1561[81] and NFPA 502 (Annex F).[82]

SRT TSI Section 4.4.2 states that an emergency plan should (1) be developed under the direction of the Infrastructure Manager, in cooperation with the emergency response services and the relevant authorities for each tunnel; (2) be consistent with the self-rescue, evacuation, firefighting, and rescue facilities available; and (3) include detailed tunnel-specific incident scenarios adapted to local tunnel conditions.

The *AREMA Manual* Chapter 12.4 lists many tunnel crises: stalled trains, loss of power, derailments, collisions, and fires. Coordinated egress and emergency escape routes should be designed into tunnels to evacuate passengers.

SRT TSI[83] covers two main types of incidents. The first type is called "hot" incidents and covers fire, an explosion followed by fire, or emission of toxic gas and smoke. These incidents are especially dangerous, as there is a time constraint on passenger evacuation because of the hostile environment. The second type is called a "cold" incident and covers collisions, derailments, and fires that have been extinguished. These incidents are dangerous but do not have the same time constraints of "hot" incidents. However, passenger panic in a "cold" incident can lead to dangerous scenarios.

Tunnel Maintenance and Inspection

Maintenance

Railway tunnel maintenance incorporates the standard practices to maintain the tunnel quality over the lifespan of the tunnel. This section includes tunnel inspection, monitoring, and maintenance activities. Maintenance typically refers to a wide range of activities that can involve simple tasks to more complex processes. While tunnel rehabilitation, large-scale repairs, and upgrades can be considered a part of a maintenance program, they are separated in this report and can be referenced in the subsequent section.

Several guidelines and standards provide details about potential defects, maintenance methods, and repair strategies.

The *AREMA Manual* (Chapter 1, Part 8) specifies the following potential defects: concrete spalls, rock falls, drainage, icing, and timber sets. Further details about tunnel inspection checklists can be found in the *AREMA Bridge Inspection Handbook*.[84]

SRI TSI Section 4.5 covers maintenance rules for railway tunnels. This includes identifying elements subject to wear, failure, aging, or other forms of deterioration or degradation; specifying the limits of use of elements subject to deterioration and describing measures to prevent this deterioration; identifying elements relevant to emergencies; and periodic checks of the emergency equipment to ensure proper functioning.

---

[83] EU 1303/2014, *op. cit*.

[84] *AREMA Bridge Inspection Handbook*, Chapter 11 – Tunnel Inspection, 2010.

The *TOMIE Manual*[85] provides details about tunnel operation, maintenance, inspection, and evaluation.

An effective tunnel maintenance program helps reduce costs, decreases the number of tunnel closures, increases public safety, and ensures adequate levels of service. Maintenance activities range from simple tasks to complex endeavors, as indicated in the hierarchy below:

- Removing debris, snow, and ice
- Washing tunnel structures, flushing drains, tightening bolts, and changing light bulbs
- Servicing equipment, painting fixtures, and restoring pavement
- Tests, verifications, measurements, and calibrations
- Planned interventions
- Unplanned interventions
- Rehabilitation (large-scale repairs and upgrades are implemented)

Tunnel operation can be divided into two parts—normal operation and emergency response. Listed below are examples for both aspects of operation.

- Normal operating procedures: maintaining traffic flows, tunnel traffic closures, studying weather conditions, clearing roadway hazards, inspecting critical areas, checking functional systems, servicing equipment, clearing of tunnel facility, maintaining vehicles and equipment, completing daily logs and checklists, processing work orders, and checking information, evaluation sensors, and meters.
- Emergency response: impacts and collisions – remove vehicles, clear debris, repair pavement, inspect tunnel damage; fires – emergency ventilation measures, rapid detection; floods – pump systems; and earthquakes – structural damage, leaks.

Ideally, the maintenance strategies of a tunnel facility should strike a balance between preventive maintenance and on-demand maintenance. If safety or structural concerns are identified in the process of carrying out maintenance tasks, then the defects should be addressed.

Inspection

Tunnel inspection requires multiple-disciplinary personnel familiar with various functional aspects of a tunnel, including civil/structural, mechanical, electrical, drainage, and ventilation components, as well as some operational aspects such as signals, communication, fire-life safety, and security components. The inspectors should be certified and know inspector responsibilities.

---

[85] FHWA-HIF-15-005, *op. cit.*

FHWA developed the National Tunnel Inspection Standards (NTIS),[86] the TOMIE[87] Manual, and the Specifications for National Tunnel Inventory (SNTI)[88] to help safeguard tunnels and to ensure reliable levels of service on all public roads. The NTIS contains the regulatory requirements of the National Tunnel Inspection Program (NTIP); the TOMIE Manual and SNTI have been incorporated by reference into the NTIS to expand upon the requirements. The TOMIE Manual is a resource for aiding the development of tunnel operations, maintenance, inspection, and evaluation programs; it provides uniform and consistent guidance. The SNTI contains instructions for submitting the inventory and inspection data to FHWA, which will be maintained in the National Tunnel Inventory (NTI) database to track the conditions of tunnels throughout the United States. The general requirements of the program can be summarized as follows:

- Performing regularly scheduled tunnel inspections
- Maintaining tunnel records and inventories
- Submitting tunnel inventory and inspection data to FHWA
- Reporting critical findings and responding to safety and/or structural concerns
- Maintaining current load ratings on all applicable tunnel structures
- Developing and maintaining a quality control and quality assurance program
- Establishing responsibilities for the tunnel inspection organization and qualifications for tunnel inspection personnel
- Training and national certification of tunnel inspectors

As detailed in Table 3-15, inspection types can be separated based on their priority: initial, routine, damage, in-depth, and special.

Table 3-15 *Inspection Types and Their Purpose*

Inspection Type	Purpose
Initial	Establish the inspection file record and the baseline conditions for the tunnel.
Routine	Comprehensive observations and measurements performed at regular intervals.
Damage	Assess damage from events such as impact, fire, flood, seismic, and blasts.
In-depth	Identify hard-to-detect deficiencies using close-up inspection techniques.
Special	Monitor defects and deficiencies related to safety or critical findings.

---

[86] FHWA, Rule 80 FR 41349, 23 CFR Part 650, National Tunnel Inspection Standards, 2015.

[87] FHWA-HIF-15-005, *op. cit*.

[88] FHWA, *Specifications for the National Tunnel Inventory*, Publication No. FHWA-HIF-15-006, July 2015. http://www.fhwa.dot.gov/bridge/inspection/tunnel/.

Inspection techniques depend on the type of components/systems to be inspected and can be arranged by engineering discipline:

- Civil/Structural elements
  - Steel: corrosion, cracks, buckles and kinks, leakage, protection system
  - Concrete: scaling, cracking, delamination, spalling, joint spall, pop-outs, mud balls, efflorescence, staining, honeycomb, leakage
  - Timber: decay, insects, checks/splits, fire damage, hollow area, leakage
  - Masonry structure: masonry units, mortar, shape, alignment, leakage
  - Liners
  - Other structural: roof girders, columns and piles, emergency corridors, interior walls, portals
  - Ceiling: hangers and anchorages, roof, ceiling girders, slabs and panels
  - Tunnel invert structures: slabs, girders, and slabs on grade
  - Joints and gaskets
  - Miscellaneous structural cracks: connections, doors, windows and frames, stairs, roof, floors, brackets and supports, machinery pedestals, finishes
- Mechanical systems
  - Tunnel ventilation: fan motors, fan drive system, fan shaft bearing, fan drive coupling, local fan controls, dampers and damper drives, sound attenuators
  - Tunnel drainage: pumps, sump pumps
  - Emergency generator systems, flood gates
  - Miscellaneous mechanical system: plumbing, HVAC
- Electrical systems
  - Power distribution and emergency power
  - Lighting and emergency lighting
- Fire detection
- Air-quality monitoring
- Cameras and safety systems
- Communications
- Fire systems
- Communication systems
- Finishes and protective coating

All general field inspection/repair notes, consisting of a chronology of events, must be kept in a bound field book or electronic recording device such as a tablet. The information contained in the field book should include notes on safety issues and discussions with contractors, operations personnel, and other interested parties. Entries into the field book must be chronological by date and time and consist of clear, concise, factual notification of events and appropriate sketches. Field records, notes, and the inspection database must be maintained in one location.

The three types of field notes required for effective inspection of tunnels are:

- General notes in field books
- Documentation of defects on field data forms
- Documentation of defects by photographs/video

The NTIS 23 CFR Part 650 Subpart E[89] is a minimum standard for the proper safety inspection and evaluation of all highway tunnels in accordance with 23 U.S. Code § 144(h) and the requirements for preparing and maintaining an inventory in accordance with 23 U.S. Code § 144(b).

Frequency of inspection based on 23 CFR Part 650 Subpart E include:

- Initial inspection prior to opening to traffic to the public.
- Routine inspection must be conducted at regular 24-month periods. For tunnels needing inspection more frequently than 24-month intervals, criteria must be established to determine the level and frequency at which these tunnels are inspected, based on a risk analysis approach that considers such factors as tunnel age, traffic characteristics, geotechnical conditions, and known deficiencies.
- Certain tunnels may be inspected at regular intervals up to 48 months. Inspecting a tunnel at an increased interval may be appropriate when past inspection findings and analysis justify the increased inspection interval. At a minimum, the following criteria should be used to determine the level and frequency of inspection based on an assessed lower risk: tunnel age, time from last major rehabilitation, tunnel complexity, traffic characteristics, geotechnical conditions, functional systems, and known deficiencies. A written request that justifies a regular routine inspection interval between 24 and 48 months must be submitted to FHWA for review and comment prior to the extended interval being implemented.

Damage, in-depth, and special inspections may use non-destructive testing or other methods not used during routine inspections at an interval established by the program manager (for example, ultrasonic inspection or electromagnetic inspection of steel components). In-depth inspections should be scheduled for complex tunnels and certain structural elements and functional systems when necessary to ascertain the condition of the element or system fully; hands-on inspections may be necessary at some locations.

---

[89] FHWA, Rule: 80 FR 41349, *op. cit*.

To track the conditions of tunnels throughout the United States and to ensure compliance with NTIS, FHWA established an NTI database to contain all the initial tunnel inventory and inspection data. The preliminary inventory includes data items described in the specifications for the NTI (incorporated by reference, see 23 CFR § 650.515) for all tunnels subject to NTIS by December 11, 2015.

NTI is an inventory of all highway tunnels subject to NTIS that includes the preliminary inventory information, reflects the findings of the most recent tunnel inspection conducted, and is consistent and coordinated with the specifications for NTI.

The Specifications for National Tunnel Inventory (SNTI) is used to collect inventory items such as tunnel identification, age and level of service, classification, geometric data, inspection, load rating and postings, navigation, and structure type. The SNTI inventory items require the item name, specification, commentary, examples, format, and alpha-numeric identification. The specification contains descriptions of each inventory item and provides a series of explanations in the commentary section.

Other references include the following:

- NCHRP Project 20-07/Task 261[90] report summarizes current inspection practices for 32 highway and 11 transit tunnel owners. The report compiled information on inspection stages, procedures, and inspector qualifications. Best practices were also included for safety and emergency response system testing.
- NCHRP Project 20-07/Task 276[91] report establishes best practices for the repair of existing tunnel elements. The report focuses on structural and drainage repairs and provides detailed recommendations on the steps of the rehabilitation process.
- Chapter 11 of the *AREMA Bridge Inspection Handbook*[92] provides information about safety precautions related to tunnels, such as lack of light throughout the tunnel, wildlife, and emergency inspections due to fire, floods, earthquakes, and derailment. It also lists tunnel inspection aspects that should be addressed related to the external environment, internal tunnel safety, drainage, natural gas, portals, and main tunnel structure (tunnel shaft). The tunnel inspection checklist includes soil/rock stability, clearances, drainage, tunnel floor, and conditions of structural components.

---

[90] NCHRP, *Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspection*, NCHRP Project 20-07, Task 261 Final Report, October 2009.

[91] NCHRP, *Development of Guidelines for Rehabilitation of Existing Highway and Rail Transit Tunnels*, NCHRP Project 20-07, Task 276 Final Report, July 2010.

[92] *AREMA Handbook*, *op. cit*.

Inspection Reports

Inspection reports are formal summaries of inspection findings for each element and system that was inspected. The report should be submitted in accordance with written procedures established by the tunnel inspection organization and the owner. The completed report should be furnished to the tunnel owner, along with any repair recommendations.

Following are examples of elements in an inspection report:

- Critical finding – refers to defects that require immediate action, including possible closure of the tunnel where safety or structural concerns are identified using criteria established in NTIS. Upon discovering a critical finding, the team leader should notify the program manager and the tunnel owner immediately. A summary of these details can be included in the inspection report as necessary.
- Priority repair – refers to conditions for which further investigation, design, and implementation of interim or long-term repairs should be undertaken on a priority basis (i.e., taking precedence over other scheduled work). These repairs will improve the durability and aesthetics of the structure or element and will reduce future maintenance costs. Elements that do not comply with code requirements are also priorities for repair.
- Routine repair – refers to conditions requiring further investigation or remedial work. This work can be undertaken as part of a scheduled maintenance program, scheduled project, or routine facility maintenance. Items identified in the preventive maintenance program can be put in this category.

A detailed description of inspection results should be included for the various tunnel elements:

- Structural and civil inspections – should follow design/construction and agency cyclic maintenance schedules and procedures. Further, the report should contain descriptions of various deficiencies, their locations, and severity. Any special test results, such as concrete strength, freeze-thaw analysis, or petrographic analysis, should be included with the findings for the record. Future recommended actions should also be noted.
- Mechanical inspections – should follow manufacturer and agency cyclic maintenance schedules and procedures. Further, the general condition and operation of all equipment should be described and the deficiencies noted. Specialized test results, such as vibration testing and oil analyses, should be included for the record. Future recommended testing and actions should also be noted.
- Electrical inspections – should follow manufacturer and agency cyclic maintenance schedules and procedures. Further, the general condition

and operation of all electrical equipment should be described and the deficiencies noted. Any specialized testing needed to effectively determine the operational condition of the equipment, such as power distribution and emergency power, should be included for the record. In addition, comparisons of light level measured to recommended levels should be provided to the owner. Remediation work that may accompany testing and inspection should be included.

Finally, recommendations for repair or rehabilitation of the tunnel components found to be deficient or that do not meet current code requirements should be identified. Substantial rehabilitation may require a life cycle cost comparison of repair options. Repair and rehabilitation recommendations should be broken down for each main tunnel system into the categories previously described: critical finding, priority repair, and routine repair.

Evaluation of Tunnels

The cost of maintaining and improving tunnel systems must be balanced against available funding. Resources are limited for making repairs and upgrades; therefore, repairs must be evaluated and prioritized to make informed investment decisions. Evaluations are normally performed after the inspection data are received. Sound engineering judgment is used to evaluate the consequences of tunnel system or component failure in terms of overall safety, service level, and costs. In some instances, supplementary inspections and testing may be needed where data are lacking. Risk assessment techniques should include strategies for deploying, operating, maintaining, upgrading, and cost-effectively disposing of tunnel system components.

Tunnel Rehabilitation

The most significant problem in constructed tunnels is groundwater intrusion. The presence of water in a tunnel, especially if uncontrolled and excessive, accelerates corrosion and deterioration of the tunnel liner. Electrical, mechanical, and drainage systems could also be affected.

Groundwater Intrusion

Groundwater intrusion can be mitigated either by treating the ground outside the tunnel or by sealing the inside of the tunnel. Selecting the proper repair procedures and products for the project's conditions, such as the degree of leakage into the tunnel from the defect, is key to the success of a leak containment program. Typically, the tunnel defects that cause leakage are construction joints, liner gaskets, and cracks that are the full depth of the liner.

- Liner – The most common way to seal a tunnel liner is to inject a chemical or cementitious grout. The grout can be applied to the outside of the tunnel to create a “blister” type repair that seals off the leak by covering the affected area. Grout selection depends on the groundwater inflow and chemical properties of the soil and water.

- • Cracks and joints – The most common method of sealing leaking cracks and joints is to inject a chemical or particle grout directly into the crack or joint. This is accomplished by drilling holes at a 45-degree angle through the defect. The holes are spaced alternately on either side of the defect at a distance equal to half the thickness of the structural element. The drill holes intersect the defect and become the path for injecting the grout into the defect. All holes must be flushed with water to clean any debris from the hole and the sides of the crack or joint before injection to ensure proper bonding of the grout to the concrete.

For joints that move, only chemical grout is appropriate. The joint or crack movement will fracture any particle grout and cause the leak to reappear. In situations where the defect is not subject to movement and is dry at the time of repair, epoxy grout can be injected into the defect in the same manner that concrete is structurally re-bonded.

Structural Repair – Concrete

- Concrete delamination – The repair of concrete delamination and spalls in tunnels has traditionally been performed by the form-and-pour method for placing concrete or by the hand application of cementitious mortars modified by the addition of polymers. Today, the repair of concrete structural elements is typically performed by two methods: hand-applied mortars for small repairs and shotcrete for larger structural repairs.
- Shotcrete – The pneumatic application of cementitious products that can be applied to restore concrete structures. Shotcrete is defined by the American Concrete Institute as a “mortar or concrete pneumatically projected at a high velocity onto a surface.” Over the years, developments in materials and application methods have made the use of polymer cementitious shotcrete products for repairing defects in tunnel liners of active highway tunnels cost-effective. The selection of the process type and material to be applied depends on the specific conditions for tunnel access and available time for the repair installation. Shotcrete is preferred to other repair methods since the repair is monolithic and becomes part of the structure. The shotcrete process allows for rapid setup, application, and ease of transport into and out of the tunnel daily.

Structural Injection of Cracks

Structural cracks that occur due to structural movement, such as settlement, and are no longer moving should be structurally re-bonded. Any crack being considered for structural re-bonding must be monitored to assess if any movement is occurring. Structural analysis of the tunnel lining should be performed to ascertain if the structural integrity was compromised and if the subject crack requires re-bonding.

Three types of resin are typically available for injecting into tunnel structural cracks: vinyl ester resin, amine resin, and polyester resin. Amine and polyester resins are best suited for the structural re-bonding of cracks in tunnels. Both resins are unaffected by moisture during installation and will bond surface-saturated concrete.

Segmental Lining Repair

The most common problem with segmental steel and cast-iron liners is deformation of the flanges due to steel corrosion. In precast concrete segments, the issue is related to the physical expansion of the corroded steel reinforcement acting on precast concrete structures resulting in corner spalling. The spalling of precast segments and deformation of the flanges of steel/cast iron segments are due to installation errors or impact damage from vehicles. In addition, rusting through of the liner plate of steel/cast iron segments occasionally occurs.

- Precast concrete segmental liner – The repair of spalls in precast concrete liner segments is performed using a high-performance polymer modified repair mortar, which is formed to recreate the original lines of the segment. If the segment gasket is damaged, the gasket's waterproofing function is restored by injecting a polyurethane chemical grout, as described above. Damaged bolt connections in precast concrete liner segments are repaired by carefully removing the bolt and installing a new bolt, washer, waterproof gasket, and nut. The bolts must be torqued to the original specification and checked with a torque wrench.
- Steel/cast iron liner – The repair of steel/cast iron liners varies according to the type of liner material. Steel, if made after 1923, is weldable, but cast iron is not. Common defects in these types of liners are deformed flanges and penetration of the liner segment due to rusting. Deformed flanges can be repaired by reshaping the flanges with hammers or heat. Holes in steel liner segments can be repaired by welding on a new plate. Bolted connections often experience galvanic corrosion caused by dissimilar metal contact, which usually requires replacing the entire bolted connection. When the bolted connection is replaced, a nylon isolation gasket prevents contact between the high-strength bolt and the liner plate. Repairs to cast iron liner segments are similar to those for steel. However, since cast iron cannot be welded, the repair plate for the segment is installed by brazing the repair plate to the cast iron or by drilling and tapping the liner segment and bolting the repair plate to the original liner segment. In some instances, it is easier to fill the area between the flanges with shotcrete.

Steel Repair

Structural steel is commonly used at tunnel portals, to support internal ceilings, columns, and segmental liners, and as standoffs for tunnel finishes. The most recent version of the American Welding Society's Structural Steel Welding Code AWSD1.1/D1.1 should be utilized for the construction of all welded steel connections. Repairs to rivets and bolting must comply with AASHTO specifications.

Masonry Repair

The restoration of masonry linings composed of clay brick or ashlar (dimension) stone consists of repointing deficient mortar. The repointing of masonry joints involves raking out the joint to a depth of approximately 1 in (2.54 cm). Once the joint has been raked clean and all old mortar removed, the joints are repointed with a cementitious mortar or with a cementitious mortar fortified with an acrylic bonding agent.

Replacement of broken, slaked, or crushed clay brick requires a detailed analysis to determine the causes and extent of the problem. Once the problem is properly identified, a repair technique can be designed for the structure. Caution must be exercised in the removal of broken or damaged brick. Removing numerous bricks from any one section may cause the wall or arch to fail. Any repair work on masonry should be performed by competent personnel with experience in restoring brick and stone masonry.

Unlined Rock Tunnels

Unlined rock tunnels do not require a permanent concrete, brick, or steel lining since the rock was competent and illustrated sufficient strength with minimal reinforcement to remain standing. These roadway tunnels are also usually very short in length. Most have various types of rock reinforcement support, including rock dowels, rock bolts, cable bolts, and other reinforcement placed at various angles to cross discontinuities in the rock mass.

Rock reinforcement elements may deteriorate and lose strength due to the corrosive environment and exposure typical in tunnels, requiring the replacement and installation of new reinforcement elements. Replacement of rock reinforcement elements requires a detailed investigation of the structural geology of the tunnel, which is performed by an engineering geologist or geotechnical engineer having experience in geologic mapping and rock stability analysis.

Another more frequent cause for the need to repair unlined rock tunnels is falling rock fragments, which become loose and drop onto the roadway over time. There are many ways to prevent this from occurring, the most common of which is to scale (remove) all loose rock from the tunnel roof and walls periodically by using a backhoe or hoe ram. Other methods include placing a steel liner roof as a shelter, adding rock bolts and wire mesh to contain the falling rock fragments, and applying shotcrete to the areas of concern.

Special Considerations for Supported Ceilings and Hangers

Suspended ceilings are generally supported by keyways in the tunnel walls and by hanger rods attached to the tunnel liner either by cast-in-place inserts or post-installed mechanical or adhesive (chemical) anchors. FHWA issued a technical advisory in 2008 strongly discouraging the use of adhesive anchors for permanent sustained tension or overhead applications. Adhesive anchors in road tunnels must conform to current FHWA directives and other applicable codes and regulations.

The inspection of these hangers is important to tunnel safety. A rigorous and regular inspection program that considers importance and redundancy is strongly recommended to maintain an appropriate level of confidence in their long-term performance. During inspections, one method to verify hangers are in tension is by “ringing” each hanger, which is done by striking it with a mason’s hammer. A hanger in tension will vibrate or ring like a bell after being struck, and a hanger not in tension because of a connection or other defect will not ring. Hangers that exhibit a defect or lack of tension should be inspected and checked for structural stability.

The repair technique of ceiling hangers depends on the type of defect. If the hanger rod, clevis, turnbuckle, or connection pins are broken or damaged, they can be replaced with similar components that match the requirements for the environment and the strength requirements of the support system.

The repair of loose connections at the tunnel arch is of primary concern. The recommended repair for failed adhesive anchors is to replace them with undercut mechanical anchors.

Section 4

Data Collection

To better understand the tunnel practices and standards used for transit rail tunnels in the United States, TTCI put forth a data collection effort to U.S. agencies. The purpose of the data collection was to (1) determine which standards are being used and (2) summarize general tunnel characteristics such as tunnel age, condition, shape, construction method, and so on. Appendix A contains the data collection sheet sent to the transit agencies. Of the 37 agencies surveyed, 17 responded indicating they own at least one tunnel.

Data Collection Results

Current Inventory

Results show a wide range of tunnel construction dates, with three tunnels built in the 1800s and six currently under construction. Figure 4-1 and Figure 4-2 present the year when construction was completed and the ages of rail transit tunnels surveyed in the United States, except for one agency that did not have the information on hand. About half of the tunnels were built more than 50 years ago, and about 15% were built more than 100 years ago. This illustrates an almost even split between newer tunnels (less than 50 years old) and older tunnels (more than 50 years old). Older tunnel infrastructure was likely not designed to incorporate recent advances in ventilation and firefighting systems, as advances have gradually improved during the past few decades.

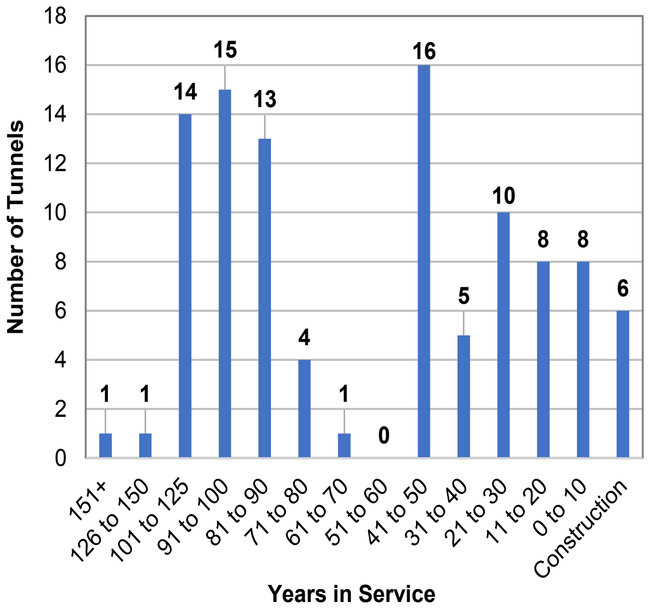


Figure 4-1 *Year of service or construction of rail transit tunnels in U.S.*

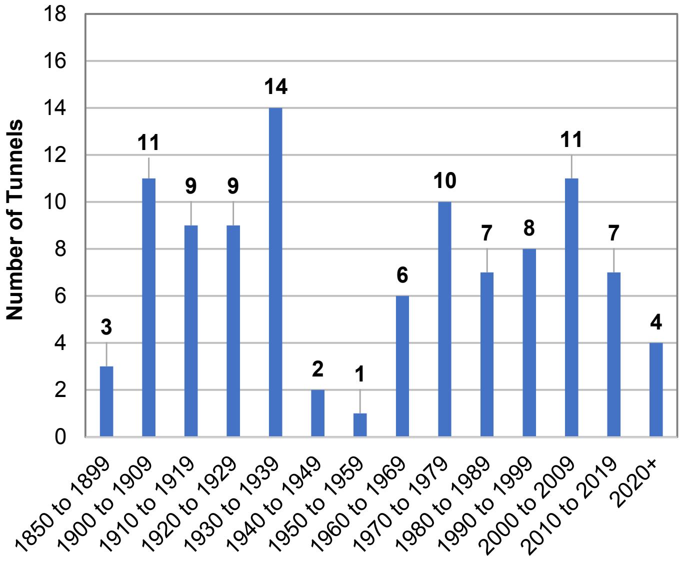


Figure 4-2 *Age of rail transit tunnels in U.S.*

Rehabilitation

Figure 4-3 shows the percentage of tunnels that experienced some sort of rehabilitation. The results show about 20% of U.S. rail transit tunnels have been rehabilitated, 47% have not, and 33% are unknown. The "yes" response includes both full and partial rehabilitation.

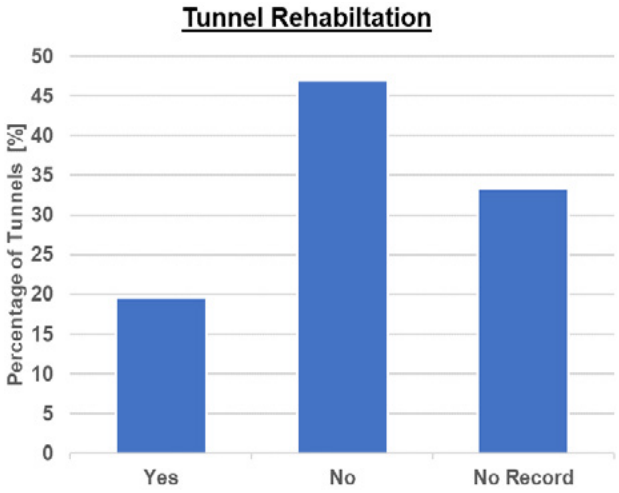


Figure 4-3 *Percentage of tunnels that have been rehabilitated*

Rail Mode

Figure 4-4 shows the rail mode that passes through each tunnel. Most tunnels (58%) have heavy rapid rail service. The rest have lower values of light rail (24%) and commuter rail (15%) service.

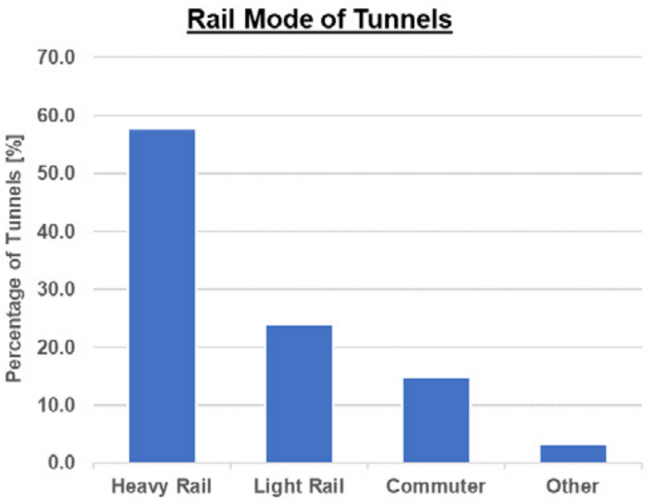


Figure 4-4 *Percentage of tunnels with each rail mode*

Construction Methods

Figure 4-5 shows various construction methods used by agencies. The percentages do not add up to 100% because more than 40% of tunnels had multiple construction methods. The results show the most common construction method was cut-and-cover, with significant portions constructed using shield-driven or boring methods.

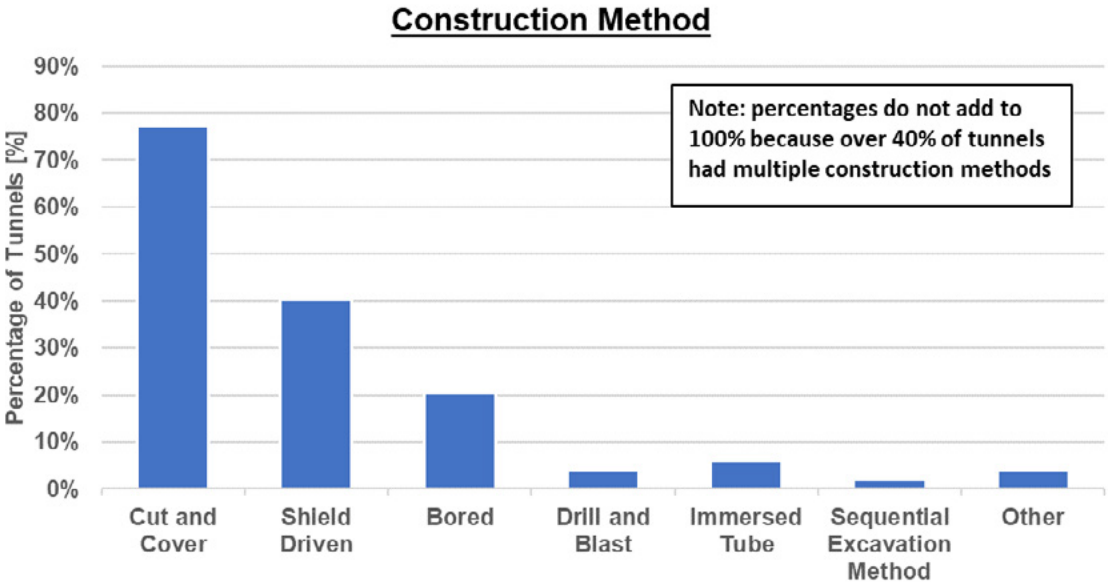


Figure 4-5 *Percentage of tunnels constructed with each construction method*

Inspection Frequencies

Concerning the frequency of tunnel inspections, Figure 4-6 shows that just over half of transit agencies with tunnels inspect their tunnels within a one- to three-year range (9 out of 17 = 50%). Two agencies (12.5%) inspect at shorter and longer intervals than the one- to three-year range.

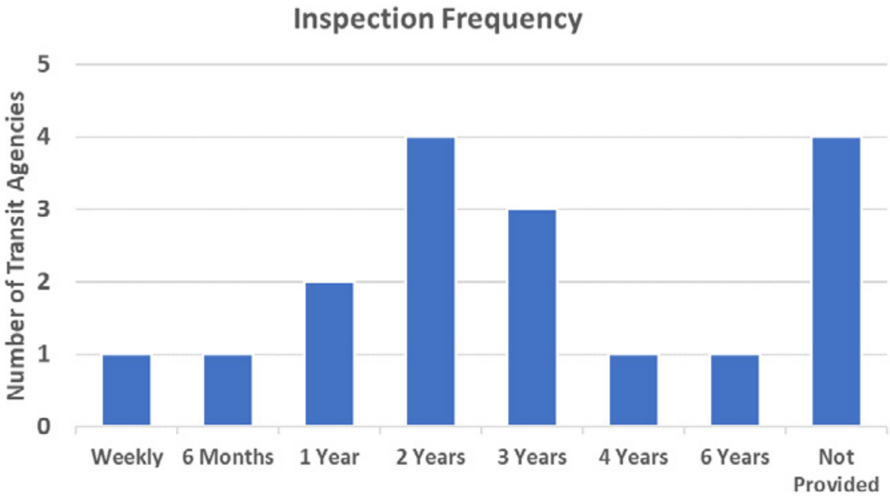


Figure 4-6 *Number of transit agencies with tunnels performing tunnel inspection at different time intervals*

Risk Assessment Plans

Risk assessment plans document the potential risks in a tunnel (e.g., fire, security, structural, mechanical, and electrical). The plans assess the magnitude of these risks to the tunnel infrastructure and the safe operation of trains, passengers, and transit agency. Figure 4-7 shows that about 25% of transit agencies with tunnels (5 out of 17) have risk assessment plans.

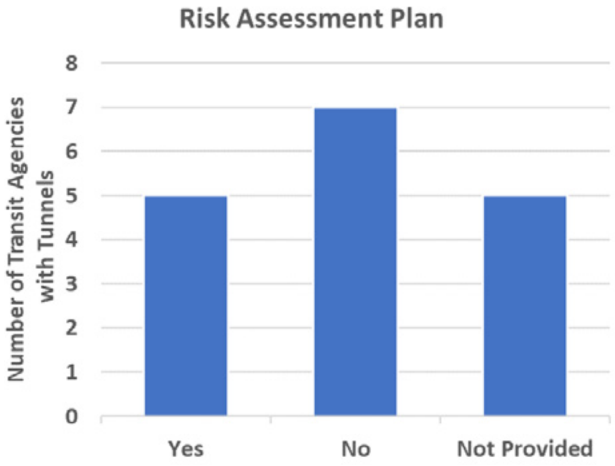


Figure 4-7 *Percentage of transit agencies with tunnels that have risk assessment plans*

Structural Design

Transit agencies with tunnels use a wide range of structural design manuals, including:

- *AREMA Manual for Railway Engineering* and *AREMA Bridge Inspection Handbook*
- US DOT/FHWA *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*
- American Concrete Institute (ACI) code 318[93] and *PCI Design Handbook*[94]
- AISC *Steel Construction Manual*[95]
- Agency standards

These standards are used about equally (Figure 4-8), and many transit agencies use multiple standards (Figure 4-9) or only their agency standards, which may be comprehensive and reference the general standards. The 56% of tunnel agencies without codes (9 out of 16) either do not plan on designing or constructing new tunnels in the near future or may outsource design to consulting companies.

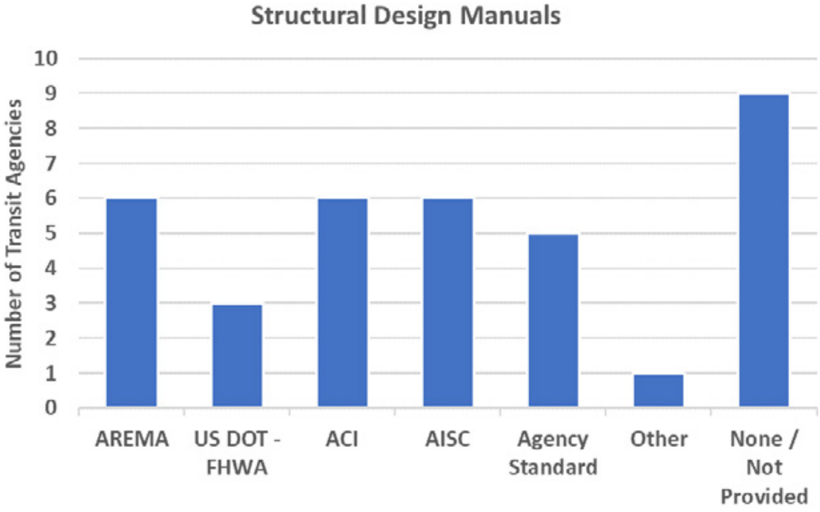


Figure 4-8 *Types of structural design manuals and number of agencies using them*

---

[93] American Concrete Institute, Building Code Requirements for Structural Concrete (ACI 318-14), Farmington Hills, MI, 2018.

[94] Precast/Prestressed Concrete Institute, *PCI Design Handbook: Precast and Prestressed Concrete*, 8th edition, Chicago, IL, 2017.

[95] American Institute of Steel Construction, *Steel Construction Manual*, 14th edition, Chicago, IL, 2011.

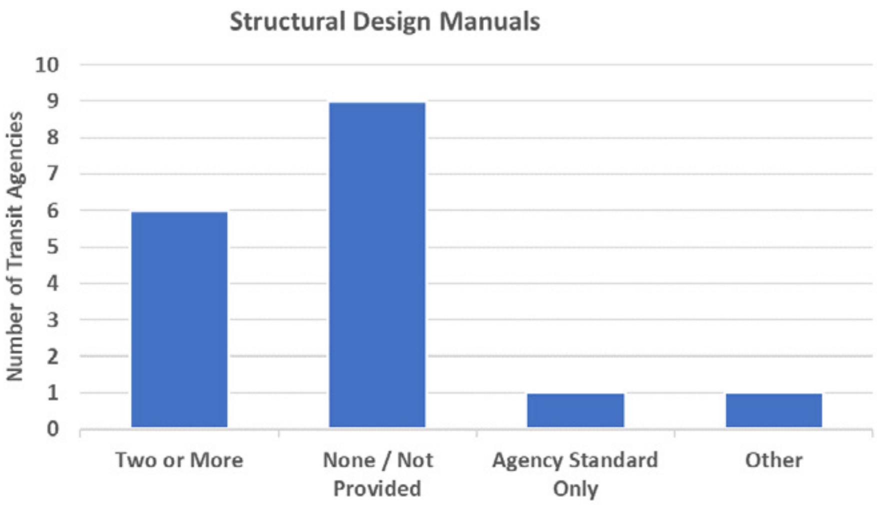


Figure 4-9 *Number of structural design manuals used and number of agencies using them*

Supporting Systems

For supporting systems design, similar distributions are found in Figure 4-10 and Figure 4-11, but additional sources are used, such as NFPA 130[96] and local codes.

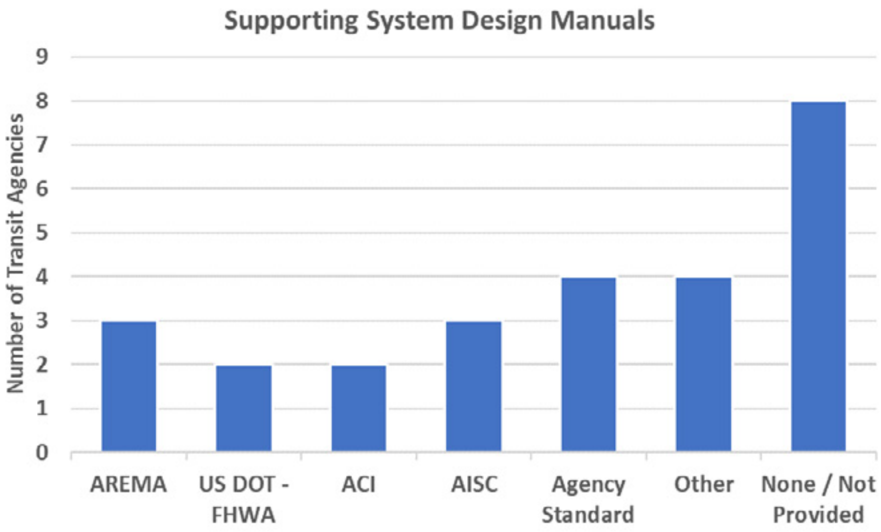


Figure 4-10 *Types of manuals for supporting system design and number of agencies using them*

---

[96] NFPA 130, *op. cit*.

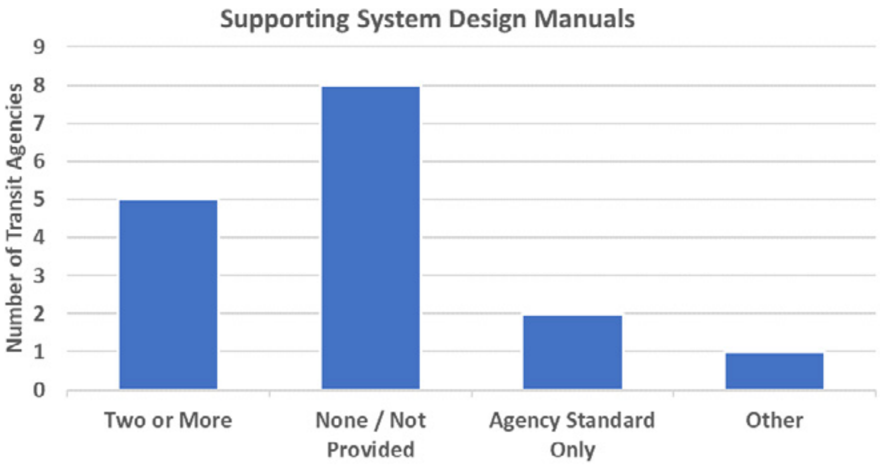


Figure 4-11 *Number of supporting system design manuals used and number of agencies using them*

Tunnel Inspection

The three most common manuals and standards for tunnel inspections are the FHWA/FTA manual,[97] *TOMIE Manual*,[98] and agency standards (Figure 4-12 and Figure 4-13).

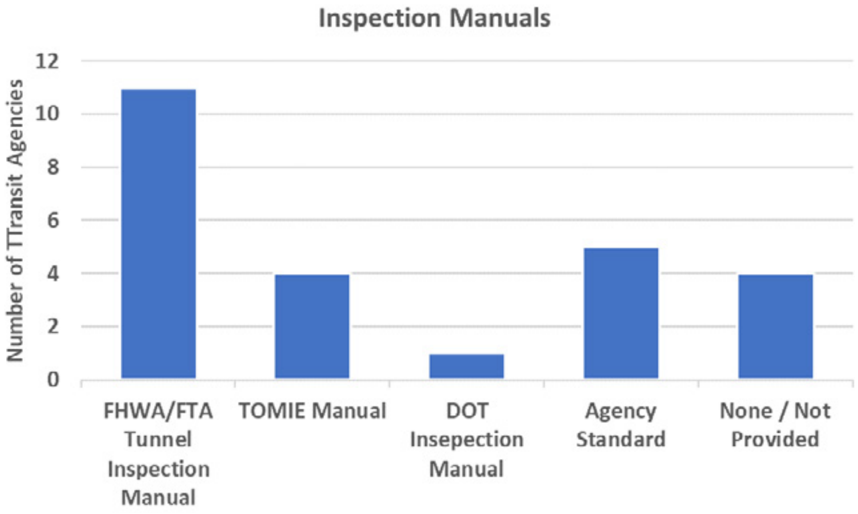


Figure 4-12 *Types of inspection manuals and number of agencies using them*

---

[97] FHWA/FTA, *Highway and Rail Transit Tunnel Inspection Manual*, 2005.

[98] FHWA-HIF-15-005, *op. cit.*

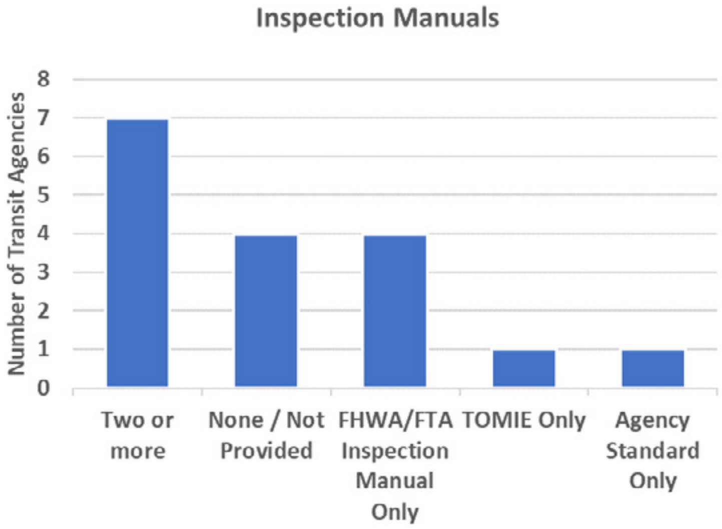


Figure 4-13 *Number of inspection manuals used and number of agencies using them*

Maintenance and Rehabilitation

Results similar to inspection manuals were found for manuals used for maintenance and rehabilitation. The FHWA/FTA *Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual* is the most common (Figures 4-14 and 4-15).

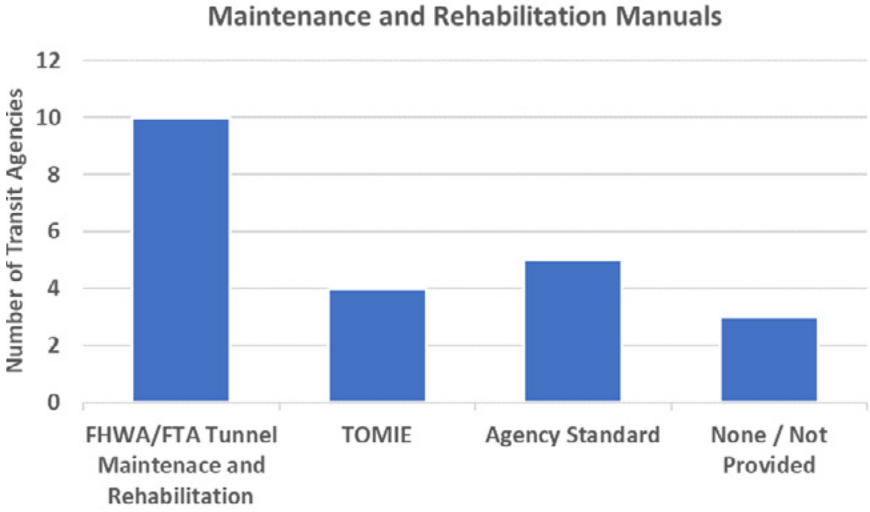


Figure 4-14 *Types of maintenance and rehabilitation manuals and number of agencies using them*

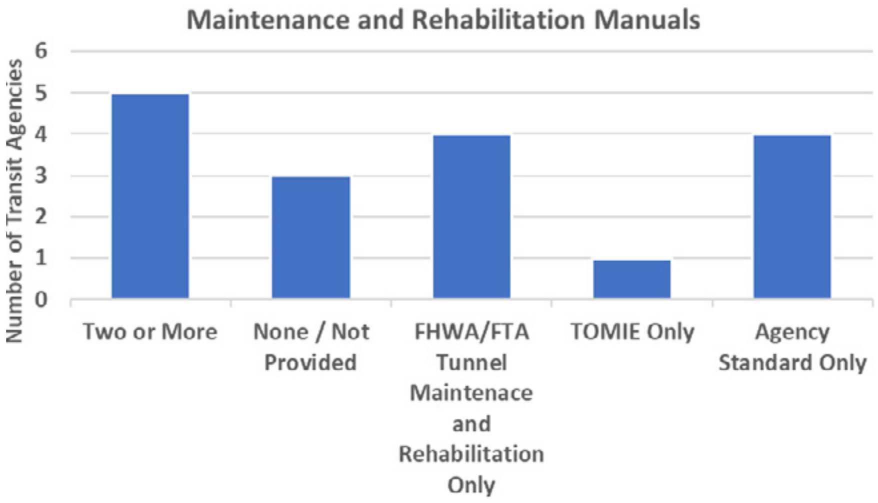


Figure 4-15 *Number of maintenance and rehabilitation manuals used and number of agencies using them*

Data Collection Summary

The results of the data collection survey give insight into the practices of various rail transit agencies regarding tunnel design, inspection, maintenance, and repair. General remarks from analyzing the results are:

- Transit agencies with tunnels have a wide range of tunnel design, inspection, maintenance, and repair practices.
- Most transit agencies use design, inspection, and maintenance manuals developed for roadway tunnels.
- Transit agencies with multiple tunnels tend to have their own agency standards. It is unclear how these standards compare against each other or against the general guidelines published by FHWA or FTA.

Section 5

Site Visits

This project included selecting five transit agencies to visit to discuss their current practices for new tunnel design and for inspection, maintenance, and repair of existing tunnels. Trips were made to both East and West Coasts and included the following transit agencies: San Francisco Bay Area Rapid Transit (BART), Los Angeles County Metropolitan Transportation Authority (LA Metro), MTA-New York City Transit Authority, Massachusetts Bay Transportation Authority (MBTA), and Washington Metropolitan Area Transit Authority (WMATA).

Visits were made to new tunnels to gather information about:

- Geotechnical aspects and structural types
- Standards used during design and construction
- Challenges encountered during construction
- Modifications required during construction

Visits to retrofitted tunnels gathered information about:

- Changes in the construction conditions
- Issues related to tunnel inspection and maintenance
- Challenges of aging structures
- Standards used for inspections and rehabilitation

BART

Transbay Tube Overview

The Transbay Tube is a 3.6-mi (5.8-km) BART underwater rail transit tunnel connecting the Market Street Subway in San Francisco with the West Oakland Station in Oakland. Construction began in 1965 and the tunnel opened for operations in 1974.

Geological Investigation

To determine the profile underneath the San Francisco Bay, numerous boring and test programs were conducted prior to construction. The geological profile was determined to be heterogeneous with different layers of alluvium and bedrock.

Structural Design

The Transbay Tube has a concrete liner that is sealed by a 0.625-in (16-mm) steel shell. The individual sections were connected using welds.

The tunnels consist of a slab track rail transit line powered by a 1,000-volt third rail located on the outside of the tunnel away from the corridors. A 2.5-ft (0.76-m) walkway is located on the side near the inner corridor.

Seismic Retrofit

Water intrusion is an important aspect in every tunnel. If leakage occurs, electrical issues may arise. The biggest challenge with the Transbay Tube is the variable stratigraphy underlying the tunnel that can produce a differential site response during an earthquake and may cause sections of the tunnel to pull apart. Liquefaction of the backfill material is a concern in that it would cause sections of the tube to become buoyant and rise. Reduced friction between the tube and backfill material would also cause added movement at the seismic joints. Further, inadequate welds holding the sections together may not sufficiently resist the tensile forces, potentially resulting in ruptures and major leaks.

Therefore, the Transbay Tube has required earthquake retrofitting on its exterior and interior. The fill packed around the tube was compacted to make it denser and less prone to liquefaction. Consequently, the distance the tube would rise due to liquefaction was reduced.

On the interior of the tube, BART began a major retrofitting initiative in March 2013, which involved installing heavy steel plates at various locations inside the tube that most needed strengthening (in four sections of 1 mi/1.6 km length total) to protect them from sideways movement in an earthquake. The 3.6 long tons (4,000 lb), 2.5-in (64-mm) thick plates are bolted to the existing concrete walls and welded together, end-to-end. Figure 5-1 shows the prefabricated plates.

Figure 5-1 *Custom-built plate-handling vehicle inside fabrication building carries steel plate used for reinforcement (bart.gov)*

The two side layers of the plates were installed in 2013. In December 2016, BART awarded a $267 million contract to perform further seismic retrofitting. In this phase, a new steel liner and higher-capacity pumps will be installed to reduce the possibility of the tube flooding, as the existing pumps would not be adequate in the worst-case seismic event. Other materials besides steel liners were considered in this project, but steel liners proved to be the best choice for the seismic retrofit.

Work is projected to begin in the summer of 2018 and is scheduled to take more than two years to complete. Service through the tube would be reduced or eliminated during the first and last three hours of the service day. The project's goal is to improve the strength of the structural components of the tunnel to resist seismic activities.

Supporting Systems

The upper gallery of the Transbay Tube houses the ventilation system typically used only in emergency situations. Other supporting systems are lighting, ventilation, drainage pumps, and fire detection systems. The tunnel is also equipped with an accelerometer-based seismic monitoring system.

Tunnel Maintenance

Since the structure was completed in 1969, minimal maintenance has been required on the Transbay Tube, except for some minor spalling of the lower gallery floor concrete, minor leaks, and rusty pumps. Typical and most common maintenance includes performing regular track maintenance; cleaning out sumps; cleaning out dust; replacing light bulbs; inspecting pumps for proper operation; checking upper gallery exhaust dampers for proper operation (monthly); and performing other low-key activities.

Cathodic protection is used to control the corrosion of the metal surface of the Transbay Tube. Structural inspection is performed every 24 months using BART agency standards. Track inspection is performed according to FRA standards.

One of the ongoing challenges of inspection and maintenance is that the Transbay Tube must remain in service. As a result, inspection and maintenance activities have a limited window from midnight to 4:00 am, restraining the time and capabilities for large-scale projects.

Inspections are typically visual-only unless a problem is noted, which would then involve more in-depth inspection methods, such as ultrasonic or electromagnetic inspection of steel components.

Overview of Fremont Central Park Subway in Oakland

Warm Springs/South Fremont is a BART station in Fremont, California. The Warm Springs Extension is 5.4 mi (8.7 km) of new track connecting the existing Fremont Station south to a new Warm Springs/South Fremont Station in the Warm Springs District of the city of Fremont. An optional future station will be located approximately midway in the Irvington District. The project alignment is presented in Figure 5-2.

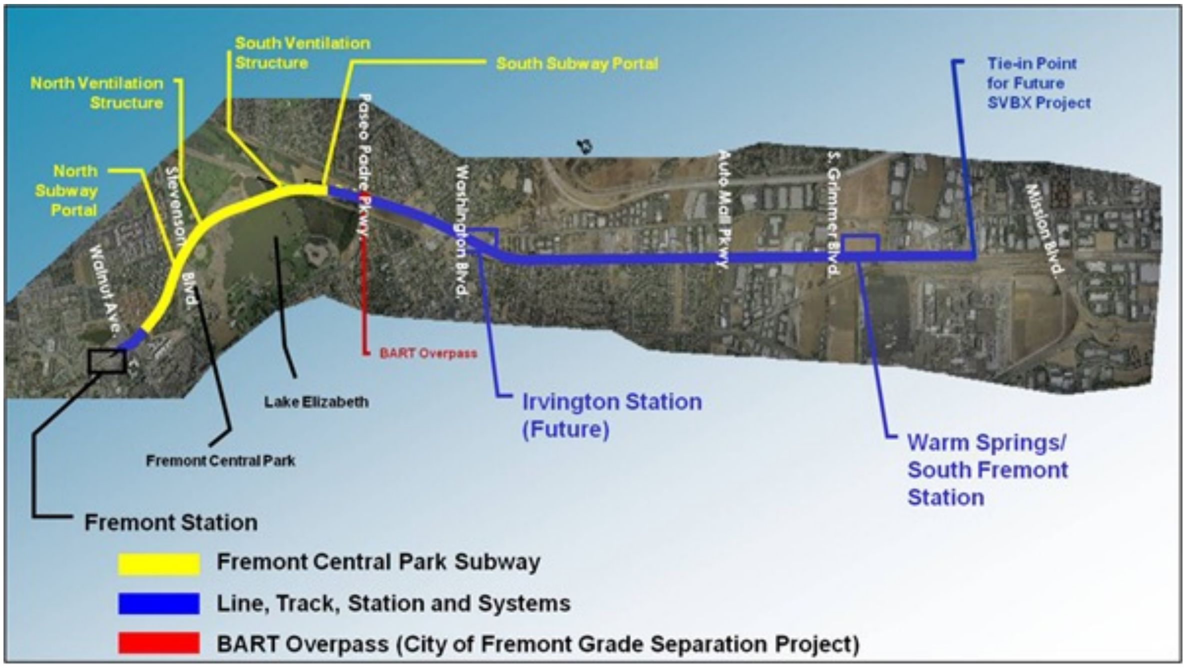


Figure 5-2 *Warm Springs extension alignment*

The Fremont Central Park subway includes a mile-long tunnel under Fremont Central Park, an embankment for the BART trackway, two ventilation structures, and the relocation of recreational facilities within Fremont Central Park. The contract work area extends from just south of Walnut Avenue, under Stevenson Boulevard and Fremont Central Park, including a portion of Lake Elizabeth, and to the east side of the Union Pacific Railroad freight tracks just north of Paseo Padre Parkway. The site visit focused on the underground subway structure of the extension.

Geological Investigation

Prior to subway design, a geological investigation was performed, which included the following activities:

- Mud rotary borings with soil sampling.
- Laboratory testing of soil samples – sieve analysis for grain size distribution, Atterberg limits[99] for plasticity, strength testing, and consolidation testing for embankment settlement.
- Cone penetration tests – specifically used to determine the top of the older alluvium as it transitions deeper as the alignment progresses toward Lake Elizabeth, providing continuous interpretation of the soils encountered to depth.
- Downhole shear wave velocities for seismic design of the cut-and-cover box – data also used to assist in the grout plug design.
- Monitoring wells – observing groundwater levels during pump testing and recording seasonal changes.
- Downhole pore water dissipation tests for permeability estimation.
- Pump test – determining the hydraulic conductivity of the young and older alluvium within Hayward Fault Aquifer.

Construction

Major construction on the Warm Springs Extension (WSX) began in August 2009 with the commencement of the Fremont Central Park Subway Contract. The Subway Contract was completed in April 2013. Major construction of the design-build Line, Track, Station, and Systems contract, which began in October 2011, was completed in the summer of 2016. The Warm Springs Extension opened for revenue (passenger) service on March 25, 2017, following a period of rigorous testing and California Public Utilities Commission approval.

Geological challenges during subway construction were related to the high-water table and mixed soil conditions: sandy young alluvium, rocky older alluvium, and crossing Lake Elizabeth. Moreover, the park functionality had to be maintained during construction activities, which limited contractor work areas.

The cut-and-cover method was used for constructing the subway based on the geological conditions and depth of the structure (relatively shallow). The lake depth at the location of the subway is only 6 ft (1.8 m).

Two types of excavation support systems were used during construction: sheet piles and cement deep soil mixing walls with soldier piles. Before excavation, a grout plug layer of up to 25 ft thick was constructed below the subway box structure.

A seasonal work restriction from October to April for Lake Elizabeth work activities presented a scheduling challenge. In addition, bird nesting (several

---

[99] https://en.wikipedia.org/wiki/Atterberg_limits.

species seen on site) delayed construction. Environmental restrictions prevented construction work within a specified radius of the nests, so if a nest was discovered, buffers were placed to reduce, limit, or prohibit access to the nesting sites. This caused minor delays, but the construction was often able to be resequenced. An example of a nest in the subway box wall construction sequence is presented in Figure 5-3.

Figure 5-3 *Nest in future concrete wall of WSX tunnel*

Structural Design

The design was performed in accordance with BART facility standards. Four seismic joints in the subway (two at each ventilation structure) were designed to mitigate potential movements during seismic activities.

The noise due to train operations was analyzed along the track using FTA criteria. Noise mitigation measures included the use of sound walls and acoustic wall treatments.

Waterproofing System

The waterproofing system was designed for roof slab, base slab, and walls. It consists of high-density polyethylene (HDPE) sheet (16 mils), geo-composite mesh (called miracle mesh), poly rubber gel (minimum 90 mils), and water-soluble membrane. During construction, the waterproofing system for the blind side application on the exterior box walls was exposed to sunlight, high temperatures up to 100°F, and sometimes extensive rain. These extreme weather conditions caused some sagging of the waterproofing poly rubber gel. The solution was to eliminate or minimize the waterproofing system exposure by doing smaller sections and covering them with protective white sheeting that reflects sunlight. The waterproofing system on walls that were damaged due to sunlight was repaired prior to pouring concrete.

Other Systems

The gravity drainage system was designed with pumps located at the low point of the subway under Lake Elizabeth.

The ventilation system was designed to pull smoke away from passenger egress routes no matter the location of the fire. The system includes two ventilation structures, each containing two fans, and it was tested along with the emergency response drills prior to the subway opening. While it was determined the piston effect is sufficient for ventilation during operations, the ventilation system is still often used during rail grinding maintenance.

Emergency egress was designed as part of evacuation routes. BART has an emergency evacuation plan and fire manual for the tunnel. The City of Fremont jurisdiction requires emergency response drills four times a year.

The Warm Springs Extension subway is equipped with a seismic alarm system in the event of quake activity and an automatic train control system to ensure safety by monitoring train movements. In addition, the subway has a security system that consists of video cameras, an imaging processing system, and an intrusion detection system.

Tunnel Maintenance

The Warm Springs Extension was opened on March 25, 2017. The periodic inspection methods used in the subway include visual inspections, ultrasonic inspections, and track geometry runs. The interval of inspection depends on the system requirements.

LA Metro Subway Tunnels

Crenshaw/LAX Line Overview

The Crenshaw/LAX line is under construction as of this writing by LA Metro, which connects the Expo/Crenshaw Station to the Aviation/LAX Green Line Station in the Los Angeles, California, metro region. The line will be 8.5 mi (13.7 km) of new track.

Construction began in June 2014 and operations are anticipated to begin in 2019. The line has a total of eight stations, three of which are underground. The project alignment is shown in Figure 5-4.

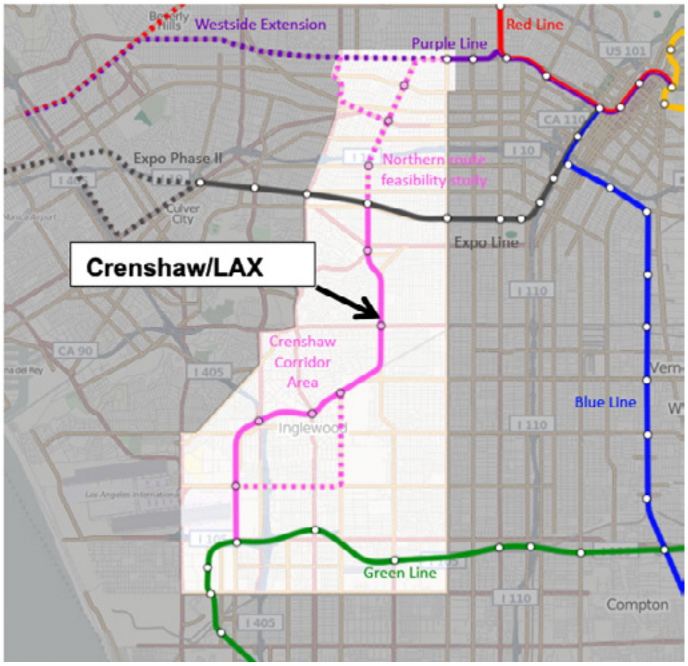


Figure 5-4 *Proposed Crenshaw/LAX line*

Geological Investigation

Prior to design and construction, geological investigations were carried out that involved sampling using sonic coring methods. This method is more expensive than typical sampling, but it was used to obtain higher quality samples using soil penetration techniques that strongly reduce friction on the drill string and drill bit due to liquefaction, inertia effects, and a temporary reduction of porosity of the soil. High-quality soil sampling helps minimize ground surface settlement, which LA Metro considered a high priority. Samples were obtained from 4–6 in (102–152 mm) diameter boreholes that extended 20 ft (6.1 m) below the bottom of the tunnel (80 ft/24.4 m below the surface) to ensure that the lower layers of soil would not present any problems. Geological investigation revealed large deposits of natural gas, which had to be dealt with during design and construction.

Construction

Three excavation methods were used for the underground lines: cut-and-cover, TBM, and SEM. The cut-and-cover method was used for transition lines that connect below-grade track to at-grade track and stations. TBM was used to connect two below-grade stations, and SEM was used for the cross passages in the TBM tunnel.

The cut-and-cover method presented many issues because the line was planned directly underneath existing road structures and disruption of traffic flow had to be minimized. The cut-and-cover excavation occurred in seven main stages. The first stage involved installing the south piles, so all traffic had to be moved to the eastbound lanes. The second stage installed the north piles, so all traffic moved to the westbound lanes. The third stage involved excavation 12 ft (3.7 m) below grade. This meant the entire street had to be closed, utilities had to be supported, and beams and decking installed. Stage four installed timber lagging to support the excavation. The remaining stages involved installing struts and incremental excavation downward. Figure 5-5 shows an example of a 60-ft (18.3 m) braced excavation.

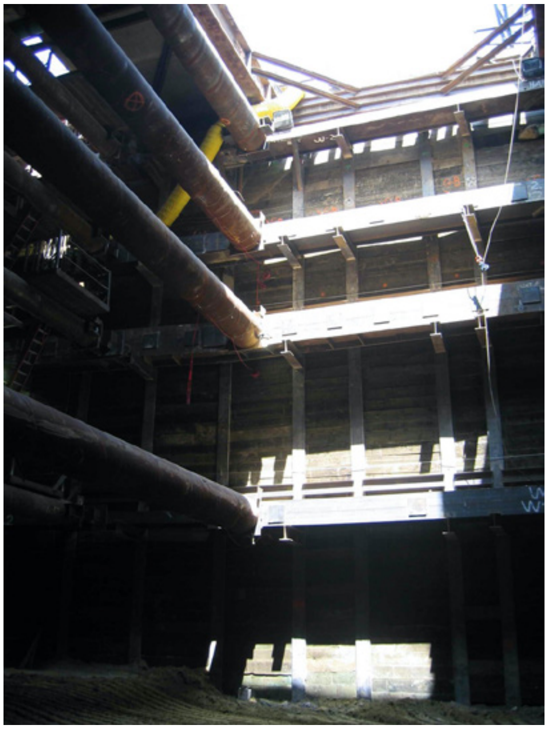


Figure 5-5 *Proposed Crenshaw/LAX line, 60-ft deep braced excavation at Mariachi Plaza (courtesy of LA Metro)*

One primary environmental issue encountered during construction was archeological discoveries. If a fossil or artifact is revealed during construction, a determination is made whether it has a value and if so, it is carefully excavated and sent to an appropriate location such as a museum. Another issue encountered during construction was the large number of utility lines underneath the road structure. These utilities had to be protected or moved. The cost of construction increased to avoid delays related to relocating the utilities.

The Tunnel Boring Machine (TBM) is used to excavate tunnels with a circular cross-section through various soil and rock strata. Urban tunneling, such as the Crenshaw/LAX line, requires the ground surface to be undisturbed. This means that ground subsidence and subsequent collapse must be avoided. TBMs with positive face control, such as earth pressure balance (EPB) machines, were used in such situations. EPB tunneling reduces the risk of surface subsidence and voids if operated properly and the ground conditions are well documented.

The machine operates by first excavating the soil in 5-ft (1.5-m) increments. This is done in a controlled manner that maintains a specified face support pressure, as shown in Figure 5-6. Afterward, pressure is maintained in the inner tunnel to reduce changes in the surrounding stress state and a liner is immediately installed. The purpose is to prevent changes in the stress state of the soil around the tunnel, therefore minimizing surface settlement.

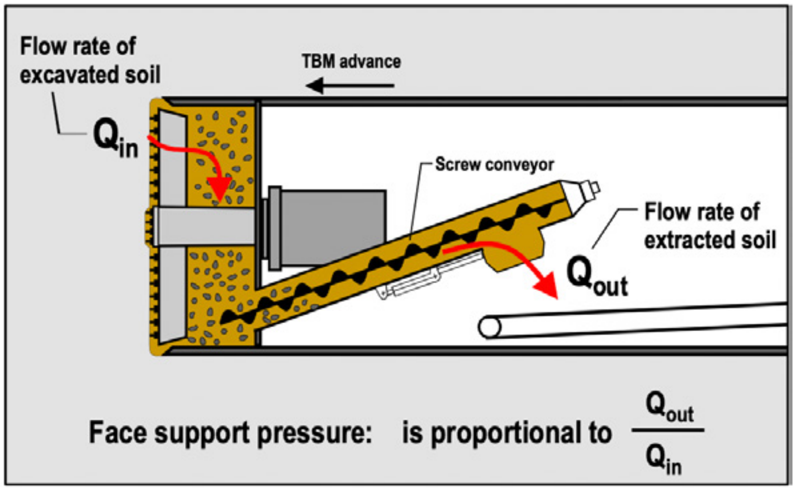


Figure 5-6 *Simplified diagram of principle of face support during TBM excavations (Courtesy of LA Metro)*

To ensure settlement reduction and to avoid sinkholes, the surface was highly instrumented and minimal settlement was recorded throughout the project. The only location with settlements above the projected goal was an area in which the TBM had temporary issues and had to be fixed.

Structural Design

The TBM Crenshaw/LAX tunnel (Figure 5-7) consists of two circular tunnels with concrete lining and cross passages. LA Metro used its own agency design standards for the design, with multiple references to the general design standards such as AASHTO LRFD, ACI, PCI, and AISC. In addition, LA Metro had a tunnel committee with three experts from academia who provided valuable comments to the project design.

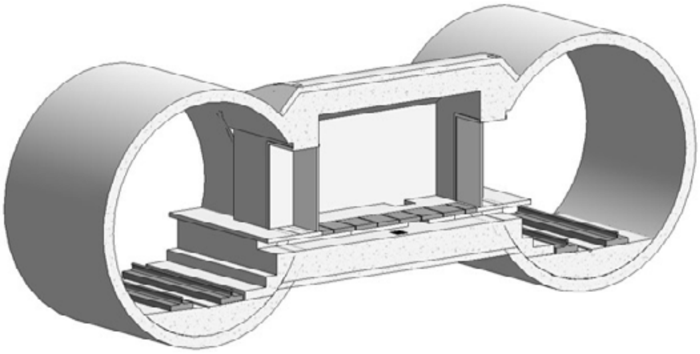


Figure 5-7 *TBM tunnel (Courtesy of LA Metro)*

Waterproofing of the cut-and-cover excavations used an HDPE membrane (Figure 5-8). The TBM tunnel has double gaskets of HDPE built into the concrete panels to prevent the infiltration of water and gas into the tunnels. Multiple pumps are used in case of water infiltration and for system and safety redundancy.

Figure 5-8 *HDPE membrane installed in station area*

Three aspects of vibration due to train movement were considered in the design process: passenger comfort, adjacent structures that could be affected, and the natural frequency of supporting systems. A special track design using springs was implemented to mitigate the potential side effects of track vibration.

Seismic Design

The seismic design keeps the tunnel in the elastic range for an ordinary earthquake, allowing for minimal plastic hinging in the occurrence of a maximum design earthquake (MDE) or a safety evaluation earthquake (SEE). Seismic joints were also incorporated into the tunnel. Tunnel lines were also designed to be perpendicular to any known faults.

Supporting Systems

The ventilation system includes booster fans installed in ceilings of certain underground segments for smoke control and four emergency fans installed in each underground station that can be activated from the rail control center, stations, or fan rooms. The station emergency fans have two modes: high-power mode for emergencies and low-power mode for typical use. The low-power mode is continuously on to vent any dirt, soot, or other contaminants that are believed to come down from the surface of stations. The fans must be turned on sequentially during emergencies to avoid overloading the electrical systems.

The Crenshaw tunnel is equipped with an alarm system to warn of seismic activity and a train control system to ensure safety. For tunnel security, gates and alarms are installed as well as high-resolution cameras to detect and track trespassers. The emergency response plan will be available after the tunnel is open for operation.

Inspection and Maintenance

The goal of LA Metro is to keep the new tunnel in a state of good repair. Structural inspections are anticipated to occur every 24 months, and LA Metro will hire consultants to conduct the inspections.

MTA–NYCT Subway Tunnels

The New York City Transit Authority (NYCT) subway system is 80 to 100 years old, and NYCT-CPM Engineering Services is responsible for the capital rehabilitation of the existing system. MTA Capital Construction agency has been tasked with managing the design and construction of system expansion projects for the past 14 years, some of which involve new tunnels such as the 7 Line West Extension and Second Avenue Subway, Phase-I, which opened January 1, 2017.

New Tunnel Overview

Design

NYCT uses its own standards, NYCT Design Guidelines (DG 452A), NY State Building Code, and NFPA 130 for tunnel structure and supporting systems. Seismic design criteria are provided in New York State Building Code Chapter 16, ASCE 7-10, and NYC DOT Seismic Design Guidelines.

The Low Vibration Track is designed to minimize the effect of train-induced vibrations.

The electrical installation in tunnels is designed according to NYCT Design Guidelines (DGs), including DGs 254 (Auxiliary Electrical Power, Lighting and Controls Engineering Design Criteria and Guidelines), 255 (Stray Current Control Design Guidelines), 256 (Power Substations Engineering Design Criteria and Guidelines), and 257 (DC Connections Engineering Design Criteria and Guidelines). NYCT also follows applicable sections of NFPA standards (e.g., Emergency Lighting), NEC, and APTA standards.

Communication standards include DG 250 (Communications Engineering Design Criteria and Guidelines), DG 259 (Fiber Optic Network Design Guidelines), and DG 312 (Flood Resiliency Design Guidelines).

Mechanical standards used for design are NFPA, AMCA, ASHRAE, and NYCT-CPM Design Guidelines (DGs), 302 (Subway Emergency Ventilation Facilities), 303 (Pump Rooms), and 312 (Flood Resiliency).

Geotechnical and Environmental Aspects

A typical geotechnical investigation program at NYCT consists of taking soil borings covering the entire footprint of the proposed alignment at approximately 100 ft (30.5 m) on centers. Additional borings may be taken at locations where soil properties are expected to change rapidly. Laboratory tests and in situ tests are conducted to obtain the required properties.

Environmental investigation follows the Environmental Site Assessment of New York City Department of Environmental Protection, with Phase 1 being the search for historical data, Phase 2 site investigation, and Phase 3 remediation. Parallel to the soil borings is a series of environmental borings to collect water and soil samples. If contaminated or hazardous material is found, Phase 3 remediation will take place during construction.

Structural Type

The shape of the tunnel is mostly dictated by the construction method. Shallow construction usually uses the cut-and-cover method, resulting in a rectangular structure. Construction in rock uses the mining method and usually results in a cavern structure with an arch ceiling and flat base. Deep construction using a TBM results in a circular structure.

The tunnel's liners are cast-in-place or precast liners depending mostly on the ability to deliver concrete to the location. NYCT's tunnels typically do not receive any finish. Stations have architectural finishes.

NYCT has dictated that only PVC waterproofing is to be used.

Supporting Systems

NYCT uses both drained and undrained tunnels. Track drains are installed and spaced at 50-ft (15-m) intervals within the track bed. Catch basins drain to a sump. Sumps are provided with three pumps—one emergency and two smaller pumps.

Passive ventilation from the piston effect due to train movement is used for daily operations, and mechanical ventilation uses fans and dampers for emergency situations. Bidirectional axial fans are typically installed to control fire/smoke in tunnels.

Communication systems include fiber optics, radios, telephones, and Emergency Alarm/Emergency Telephone (EA/ET).

For train control (signals), the Second Avenue Subway (SAS) Phase 1 is built with conventional wayside signaling system. SAS Phase 2 will be built with communication-based train control (CBTC), and MTA-NYCT will retrofit Phase 1 with CBTC.

Changes in Project during Development Process

The development (design) processes include conceptual, preliminary, and final phases. Changes are made during each phase of the design process and are incorporated into the design. This is a standard design process.

Risk Assessment Plan

The SAS Phase 1 Project (not the tunnel itself) has a risk register developed during the design phase and carried over to the construction phase.

Construction

The biggest challenge is the coordination and integration between contracts and between trades. Changes during construction usually have cost and schedule impacts and are performed under change orders.

Maintenance Handbook

Each contract provides Operation and Maintenance (O&M) manuals and conducts training sessions on all systems installed under the contract.

Emergency Response Plan

NYCT Policy Instruction 10.32.3 describes Procedures for Response to Rapid Transit Emergencies. Tunnel emergencies are part of the policy. Also, the Office of System Safety has an Emergency Action Plan that covers tunnels.

Existing Tunnel Overview

Standards Used for Inspections and Rehabilitation

For rehabilitation of tunnel structures, NYCT follows its own standard (NYCT DG-452/452A, Structural Design Guidelines/Underground Structures), the *AREMA Manual for Railway Engineering* where applicable, and ASCE 7 (Minimum Design Loads and Associated Criteria for Buildings and Other Structures).

Inspection Techniques and Frequency

NYCT performs tunnel inspections at one-year intervals. This involves four groups that inspect the tunnel structures every night during non-revenue hours. Several other departments inspect different aspects of tunnels, such as lighting, track, track drainage, traction power, and signals.

Visual inspections are typically performed on foot, but some advanced techniques are also used in specific circumstances. Ground-penetrating radar (GPR) and infrared scanning were used in the post-Sandy Montague Tunnel inspection/rehabilitation with varying degrees of success to locate voids and trapped water in the liner.

Inspection Findings and Maintenance

The most common inspection finding is groundwater intrusion in the form of leakage (Figure 5-9). The tunneling system is located below the water table, making the leakage difficult to eliminate. The current groundwater intrusion remedy is chemical grouting of box and horseshoe tunnels. A product known as No-H2O was successfully used at cast iron rings in Steinway Tubes to stop minor leakage at ring segment joints and bolts. NYCT is interested in new waterproofing technology and inspection tools to identify the source of leakage (location of damaged or deteriorated waterproofing membranes).

In addition to groundwater intrusion, the NYCT tunneling system is exposed to salt water. Flooding after Hurricane Sandy left behind salt that accelerates corrosion if wetted. Surface street water that falls through ventilation shafts is another source of salty water.

Figure 5-9 *Example of leakage and corrosion on beam (view from station)*

Other inspection findings include missing bolts, concrete spalling, and corrosion of steel components. The deterioration is more visible near ventilator banks.

After each inspection, the action items are sent to the maintenance group for repairs. If the items are small and low budget, the in-house group will perform scheduled maintenance. If the findings are complex and require a higher budget and more expertise, the project will be awarded to an outside contractor.

Due to operational demands, the challenges for inspection and maintenance are related to the available time and clearance. It is difficult to perform inspections in short periods during non-revenue hours. It is also very difficult to obtain exclusive track rights and construction time for more complex projects. The tunnel clearance is often limited, especially in older tunnel structures, which were not designed with 3-ft (0.9-m) walkways as required in current standards.

Supporting Systems

The most common issue for tunnel supporting systems is security intrusions from stations and emergency exits.

The communications maintenance in tunnels includes EA/ET and under-river tube security systems (intercoms, access intrusion control, and laser intrusion detection).

The tunnel supporting systems that need to be retrofitted or rehabilitated are fiber optics, radiating antenna/radio systems, telephone cabling, and EA/ET.

The recommendation for new tunnel design from CPM Communications is to make tunnels larger to allow right-of-way equipment to be installed more easily. It includes facilities for installing active, powered communication equipment.

Rehabilitation

The primary purpose of structural rehabilitation is to restore structural elements (steel/concrete— beams, columns, ceilings, walls, etc.) to a state of good repair and to protect against future deterioration.

Structural repairs, in general, consist of reinforcing existing steel beam and column elements via the addition of structural steel sections (plates, angles, channels, etc.) and restoring concrete elements by removing loose/deteriorated concrete and placing new concrete or patching spalls with repair mortar (e.g., epoxy grouting).

New materials are similar and generally compatible with historical materials (primarily structural steel and concrete). New steel is normally of higher strength than historic steel; likewise, new concrete, with additives to enhance durability, control shrinkage, and facilitate placement in remote and difficult-to-access locations.

Safety concerns with potentially hazardous materials are investigated during the design phase. All tunnel areas affected by the proposed construction project are surveyed to determine if asbestos containing materials are present. Based on survey findings, an asbestos abatement design is developed and the abatement is performed by NYCT’s indefinite quantities contractor or a subcontractor hired by the general contractor for a specific project. Lead paint and power cables that contain lead and insulating oil and light bulbs containing mercury can also be found within the tunnels. Specifications for the removal and disposal of these materials are included in the contract documents. Dust control specifications are incorporated in contracts where there is a potential for silica dust to be generated, such as projects where concrete demolition takes place.

Recommendations for New Design Tunnels Based on Older Tunnel Examples

Overall, NYCT tunnels (some more than 115 years old) have performed remarkably well (i.e., steel-framed cut-and-cover boxes, under-river cast iron rings), especially the waterproofing. Corrosion is evident where surface ventilators allow the entry of water (runoff) laden with winter deicing salts into various box tunnel segments or where waterproofing has been compromised (e.g., during subsequent projects). For new tunnels, assurance of proper waterproofing system installation is critical.

MBTA Subway Tunnels

Boston has the oldest continuously working streetcar system in the world. Streetcar congestion in downtown Boston led to the subways in 1897 and elevated rail in 1901. The Tremont Street Subway was the first rapid transit tunnel in the United States (120 years old). Opened in September 1897, the four-track-wide segment of the Green Line tunnel between Park Street and Boylston Stations was the first subway in the United States and has been designated a National Historic Landmark. The downtown portions of what are now the Green, Orange, Blue, and Red Line tunnels were all in service by 1912. The newest tunnel was built in 2007.

The subway system has three heavy rail rapid transit lines (Red, Orange, and Blue Lines) and two light rail lines (Green Line and Ashmont–Mattapan High-Speed Line, designated an extension of the Red Line).

Existing Tunnel Overview

Standards Used for Inspections and Rehabilitation

MBTA is currently developing an inspection handbook for their tunnels. The agency is using the FHWA/FTA 2005 *Tunnel Inspection Manual*[100] and *TOMIE Manual*[101] as a background for its handbook.

Inspection Techniques and Frequency

The inspection frequency varies and is usually limited to visual inspection, with some tunnels inspected only once every four years. MBTA contracts a consulting company to perform tunnel inspections. Special inspections are also performed using GPR and laser scans, but only in restricted locations since the new technologies are cost prohibitive.

---

[100] FHWA/FTA Manual, *op. cit*.

[101] FHWA-HIF-15-005, *op. cit*.

Inspection Findings and Maintenance

The most common inspection finding is groundwater intrusion in the form of leakage (Figure 5-10) that creates electrical issues and component deterioration. The water source depends on the tunnel location, but some leakages leave a white residue from salty water (Figure 5-11). This brings complications such as accelerated corrosion and deteriorated concrete (Figure 5-12). Salt water infiltration is difficult to mitigate. Even if the concrete crack is repaired, the salt backlog in the small cracks will lead to accelerated corrosion and concrete deterioration.

Other issues related to tunnel exploitation are brake dust and trash collection, as both can lead to a fire in a tunnel.

Figure 5-10 *Leak on tunnel wall, deteriorated concrete, and exposed rebar*

Figure 5-11 *Leak on tunnel ceiling, efflorescence confirms salt in water*

Figure 5-12 *Deteriorated concrete columns*

Tunnel maintenance includes crack injection to mitigate leaks, patching spalling concrete (Figure 5-13), coating steel components, or replacing small steel components that are rusted (Figure 5-14). MBTA has an on-call contractor performing the maintenance repairs.

Figure 5-13 *Example of spalling concrete from tunnel ceiling*

Figure 5-14 *Example of deteriorated steel columns*

Rehabilitation

The purpose of rehabilitation is to restore structural elements to a state of good repair. MBTA is looking for a rating system to help schedule its tunnel rehabilitation. Some tunnels are already 100 years old and will require major repairs soon.

MBTA has not performed a full rehabilitation on any of its tunnels. The largest maintenance work performed was to replace some steel columns that were severely corroded. Future rehabilitation projects will be scheduled based on the tunnel condition and available budget.

Maintenance and Rehabilitation of Supporting Systems

Different departments are responsible for inspecting and maintaining supporting systems: the power department for cable inspection, signal department for communication and signals, railroad engineers for track inspection, and external companies for ventilation, drainage, and pump stations. Inspections are performed yearly or biyearly, depending on the system. Exemptions are the electrical department, which performs inspections every two years, and life safety inspection, which is performed every five years and includes inspecting egress and hatches.

MBTA Lessons Learned and Recommendations for Future Projects

- Design and build tunnels to be waterproof.
- New design should consider how to inspect and maintain the structure.
- Make the clearance bigger for utility structures and maintenance purposes.
- Standards and regulations should not include too many details nor be too rigorous because they will be too difficult to accomplish and will not work.
- List of materials available for use during a repair along with their application protocol. The list will help in making repair method decisions.

WMATA Subway Tunnels

The Washington Metropolitan Area Transit Authority (WMATA) system of tunnels is about 50 years old, with the newest tunnel built about 20 years ago.

New Tunnel Overview

Design

WMATA uses its own structural design standards, based on the allowable stress design (ASD) method. WMATA engineers prefer the ASD method as they consider it more conservative than the LRFD method.

The old allowable stress design compared actual and allowable stresses, whereas LRFD compares required strength to actual strengths. The difference between looking at strengths versus stresses does not present much of a problem since the difference is normally just multiplying or dividing both sides of the limit state inequalities by a section property, depending on which way you are going. However, there are more differences between ASD and LRFD, the second major difference involving how the relationship between applied loads and member capacities is handled. The LRFD specification accounts separately for the predictability of applied loads using load factors applied to the required strength side of the limit state inequalities and for material and construction variabilities through resistance factors on the nominal strength side of the limit state inequality. The ASD specification combines the two factors into a single factor of safety. By breaking the factor of safety into the independent load and resistance factors (as done in the LRFD approach), a more consistent effective factor of safety is obtained, which can result in safer or lighter structures, depending on the predictability of the load types being used.[102]

The WMATA tunnels are not in a seismic zone so the design does not cover seismic load.

The shape of a new tunnel is mainly dictated by the construction method. Shallow construction usually uses the disruptive cut-and-cover method, typically resulting in a rectangular structure. Deeper, longer structures use TBM, resulting in a circular shape. If the tunnel is shorter, NATM (New Austrian Tunneling Method) is used.

The tunnel liners are usually cast-in-place concrete, but there is also a small percentage of steel liners (~5 %) and precast liners (~5 %). WMATA tunnels do not receive finish even within the station area.

The risk assessment plan is created during the design and construction phase.

Construction

Every new tunnel project has a general geological consultant to develop a comprehensive geotechnical study, including a water table profile.

Changes are considered at different stages during the design and construction process, and if the proposed change is beneficial, it could be implemented.

The biggest challenge during construction was building and extending a complex tunneling system through differing subsurface strata under the Washington, D.C., metro area. In addition, tunneling construction faced issues such as archaeological findings, water breakage, and misalignment. These challenges usually cause modifications in construction design and methods, extended schedules, and added costs.

Waterproofing System

The waterproofing system is important in every underground structure. Depending upon the construction type, different waterproofing systems are used in WMATA tunnels. For example, the TBM tunnel waterproofing is installed between two layers of concrete liners (precast concrete initial lining and cast-in-place concrete final lining). The waterproofing membrane consists of geotextile,

---

[102] https://www.bgstructuralengineering.com/BGDesign/BGDesign05.htm.

geomembrane, and geo-drain. If the membrane deteriorates, the leakage will be released in a designed interior location through a 3-in (76-mm) PVC weep hole. The weep hole is installed in every unit. If leakage occurs, the location will be easy to find and the leakage will be easier to mitigate.

Supporting Systems

Every tunnel contains a drainage pipe beneath the track slab that discharges water by gravity to a drainage pumping station located at the lowest points in the tunnel profile. Tunnels have passive ventilation shafts to handle the piston effect from train movement and mechanical ventilation systems consisting of ducts, shafts, and fans for emergency situations. Fans may be reversible and centrally controllable to direct the airflow away from stranded trains. Emergency procedures for trained operational personnel and regular ventilation maintenance checks, testing, and repairs are essential to ensure fans work properly during an incident.

Every tunnel is equipped with a security system that includes high-speed video cameras, intrusion alarms, and gate sensors. Further, security systems are typically monitored and recorded locally and from central command stations. The traditional fixed-block train control system of blocks and signals is maintained.

Emergency Response

Emergency response procedures and an emergency response plan are prepared for each new tunnel. Emergency response drills are performed in the tunnel itself and in a training tunnel and train simulator. The tunnel is used by the agency and other outside fire and rescue agencies. WMATA owns the training tunnel that was designed to provide a realistic training environment for fire, police, and emergency response departments from local and national jurisdictions. Located at the Carmen Turner Facility in Landover, Maryland, the facility is available for emergency response departments to use in mock fire and rescue exercises, disaster drills, and other simulations. The tunnel training facility is the first one built in the United States.

Existing Tunnel Overview

Standards Used for Inspections and Rehabilitation

WMATA is using the TOMIE Manual for inspection. Visual inspections are typically performed by personnel walking through the tunnels, but some advanced techniques are also used when more complex issues arise in specific locations.

Inspection Techniques and Frequency

WMATA has a group of qualified inspectors who inspect tunnels every weekend to ensure that every tunnel in the system has completed a yearly inspection.

Inspection Findings and Maintenance

The most common inspection finding is groundwater intrusion in the form of leakage, especially in older tunnels constructed without waterproofing membranes or because the membranes have deteriorated. Tunnels constructed after 1987 used NATM, also known as SEM (Sequential Excavation Method). These tunnels have a waterproofing system that performs well, and water intrusion is not an issue. The TBM tunnel waterproofing is installed between two layers of concrete liners (precast concrete initial lining and cast-in-place concrete final lining).

The most typical maintenance performed in the tunnels is related to leak mitigation, injecting concrete cracks, coating steel liners and components to protect them from corrosion, and replacing missing bolts. WMATA is satisfied with its technologies to inject cracks but is interested in new materials and technologies that could further improve long-term performance.

WMATA is also interested in new technologies that will help estimate steel component thickness and percentage of corrosion. The steel liner panels are usually 0.5-in (12.7-mm) thick and the steel ribs are 1-in (25.4-mm) thick. The corrosion could start on the side that is not visible, making them difficult to inspect; therefore, a technology that can help estimate the remaining steel thickness will be valuable for evaluating structures for rehabilitation.

Rehabilitation

WMATA has not performed a full rehabilitation of any of its tunnels. The biggest maintenance work effort involved replacing structural steel panels that were severely corroded. WMATA does not have any plans for major rehabilitations in the foreseeable future.

Recommendations for New Design Tunnels Based on the Older Tunnel Examples

For new tunnels, WMATA recommends ensuring redundancy of design structure and supporting systems.

Section 6

Standards Gap Analyses: Structural, Construction, Support Systems, Inspection and Maintenance, and Rehabilitation

The previous sections provided a comprehensive literature review of standards, guidelines, and best practices for rail transit tunnel structural design, construction, supporting system design, inspection, and rehabilitation, along with a data collection analysis studying the documents and practices used by various rail transit agencies in the United States. This section lists existing standards and guidelines gaps discovered from the literature review, site visits, and data collection.

Gap Analysis in Standards

The literature review references multiple standards and recommended practices available for rail tunnels. However, rail tunnels have unique aspects that need to be addressed. Therefore, the topics were categorized into the following:

- Structural Design and Construction
- Maintenance, Inspection, and Rehabilitation
- Supporting Systems
- Security and Risk Assessment

Several documents were selected as the lead documents in each category (Table 6-1). These documents cover the topic in detail and are often referenced by other documents in the same category. However, some of the selected standards are focused on road tunnels instead of rail tunnels. Most of the selected documents are from the United States and one document is from the European Union.

Table 6-1 *Main Standards for Rail Tunnels*

Category	Document	Comment
Supporting Systems/ Security and Risk Assessment	TSI No. 1303/2014	Comprehensive document focuses on rail transit passenger egress with regulations on supporting systems. The standard is from the European Union.
Supporting Systems/ Security and Risk Assessment	NFPA 502[103]	Comprehensive document focuses on road tunnel fire safety with standards on supporting systems. The standard is from the United States.
Supporting Systems/ Security and Risk Assessment	NFPA 130	Comprehensive document focuses on railway transit fire safety with standards on supporting systems. This standard includes tunnels and is from the United States.

---

[103] NFPA 502, *op. cit.*

Category	Document	Comment
Security and Risk Assessment	APTA SS-SIS-RP-16-15	Document contains guidelines and best practices for tunnel security.
Structural Design and Construction	*AREMA Manual for Railway Engineering*, Chapters 1, 8, 9	Document provides overall guidelines but lacks details.
Structural Design and Construction	AASHTO LRFD, 2017, 1st edition[104]	Comprehensive document contains details about design. The standard is for road tunnels. Most subjects are also applicable to rail tunnels, but some aspects of rails operation are missing.
Structural Design and Construction	NCHRP Report 611[105]	Document addresses seismic design.
Structural Design, Construction, and Rehabilitation	FHWA-NHI-10-034[106]	Comprehensive document contains details about design and rehabilitation. The standard is for road tunnels. Most subjects are also applicable to rail tunnels, but some aspects of rail operation are missing.
Maintenance, Inspection, and Rehabilitation	*AREMA Bridge Inspection Handbook*[107]	Document provides overall guidelines but lacks details.
Maintenance, Inspection, and Rehabilitation	FHWA-HIF-15-005[108]	Comprehensive document contains details about design. The standard is for road tunnels. Most subjects are also applicable to rail tunnels, but some aspects of rail operation are missing.
Maintenance, Inspection, and Rehabilitation	23 CFR Part 650 (2015)[109]	Minimum standard for highway tunnels. Most subjects are also applicable to rail tunnels, but some aspects of rail operation are missing.

Structural Design

The rail transit tunnel structure should be designed for a specified limit state to achieve the objectives of constructability, safety, and serviceability with respect to inspectability, maintenance, and economy issues. The first edition of AASHTO's *LRFD Road Tunnel Design and Construction Guide Specifications*, published in 2017, is the most comprehensive structural design document for tunnels. Despite being focused on road tunnels, AASHTO provides complete lists of load and load combinations, design requirements for structural materials, geotechnical information, initial ground support details, ground stabilization/improvement, and seismic considerations. Further, the reference details cut-and-cover structures, mined/bored tunnels, and immersed tunnels. All these aspects of road tunnel design are largely applicable to rail transit tunnel design with consideration to the peculiarities of rail loads, vibration, and egress requirements. The AASHTO LRFD Guide can be adapted for rail transit tunnel design. Additional documents that focus on specific aspects of rail tunnel structural design are listed in Table 6-2.

---

[104] AASHTO LRFD, *op. cit*.
[105] NCHRP, *Seismic Analysis and Design of Retaining Walls, Buried Structures, Slopes, and Embankments*, NCHRP Report 611, Transportation Research Board, 2008.
[106] FHWA-NHI-10-034, *op. cit*.
[107] AREMA Handbook, *op. cit*.
[108] FHWA-HIF-15-005, *op. cit*.
[109] FHWA 23 CFR Part 650, *op. cit*.

Table 6-2 *Additional Documents for Structural Design of Rail Transit Tunnels*

Main Topic	Documents	Applicability
Geometric Requirements	AASHTO LRFD, 2017, First Edition	Codes/standards and guidelines fully applicable.
Geometric Requirements	Transit Agency Standards	Codes/standards and guidelines fully applicable.
Geometric Requirements	FHWA-NHI-10-034 *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*	Codes/standards and guidelines fully applicable.
Geometric Requirements	*AREMA Manual for Railway Engineering*, Chapters 1 and 28	Codes/standards and guidelines fully applicable.
Geometric Requirements	SRT TSI Section 4.2.16	Codes/standards and guidelines fully applicable.
Structural Component Design	AASHTO LRFD, 2017, First Edition	Codes/standards and guidelines fully applicable.
Structural Component Design	Transit Agency Standards	Codes/standards and guidelines fully applicable.
Structural Component Design	ACI 318-08	Supplementary standards and guidelines.
Structural Component Design	ACI-224R	Supplementary standards and guidelines.
Structural Component Design	*PCI Design Handbook*	Supplementary standards and guidelines.
Structural Component Design	AISC *Steel Construction Manual*	Supplementary standards and guidelines.
Structural Component Design	AWSD1.1/D1.1 Structural Welding Guide	Supplementary standards and guidelines.
Structural Component Design	ASCE-SEI Design of Wood Structures	Supplementary standards and guidelines.
Structural Component Design	ASTM and ANSI	Supplementary standards and guidelines.
Seismic Design	AASHTO LRFD, 2017, First Edition	Codes/standards and guidelines fully applicable.
Seismic Design	Transit Agency Standards	Codes/standards and guidelines fully applicable.
Seismic Design	NEHRP Requirements	Supplementary standards and guidelines.
Seismic Design	AASHTO *Guide Specifications for LRFD Seismic Bridge Design*	Supplementary standards and guidelines.
Seismic Design	NCHRP Report 611	Supplementary standards and guidelines.
Seismic Design	*AREMA Manual for Railway Engineering*, Chapter 9	Supplementary standards and guidelines.

Construction

Tunnel construction involves excavating the native material and assembling the tunnel structure in its desired location. The process is highly variable and depends on geological conditions and the level of disruption allowed in the surrounding environment.

AASHTO's LRFD Road Tunnel Design and Construction Guide Specifications, developed based on the FHWA *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*, is the primary document for construction standards. These two documents describe construction methodologies along with information about support of excavation, structural system, specific loads and structural design, groundwater control, and other specific aspects.

Additional documents that focus on specific aspects of construction are listed in Table 6-3.

Table 6-3 *Additional Documents for Construction of Rail Transit Tunnels*

Main Topic	Documents	Applicability
Excavation Methods	AASHTO LRFD, 2017, 1st edition	Codes/standards and guidelines fully applicable.
Excavation Methods	Transit Agency Standards	Codes/standards and guidelines fully applicable.
Initial Supports	AASHTO LRFD, 2017, 1st edition	Codes/standards and guidelines fully applicable.
Initial Supports	Transit Agency Standards	Codes/standards and guidelines fully applicable.
Tunnel Lining	AASHTO LRFD, 2017, 1st edition	Codes/standards and guidelines fully applicable.
Tunnel Lining	Transit Agency Standards	Codes/standards and guidelines fully applicable.
Tunnel Lining	*AREMA Manual for Railway Engineering*, Chapter 8	Supplementary standards and guidelines.
Tunnel Lining	SRT TSI, Section 2	Supplementary standards and guidelines.
Tunnel Lining	FHWA *TOMIE Manual*	Supplementary standards and guidelines.
Ventilation during Construction	*AREMA Manual for Railway Engineering*, Chapter 12 Part 4 and Chapter 1 Part 8	Codes/standards and guidelines fully applicable.

Support Systems

Supporting systems standards primarily focus on safety to ensure passenger egress and emergency response access during emergency situations. NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems is recommended as the most relevant supporting system document covering rail transit tunnels. NFPA 130 is already implemented by many U.S. agencies or included within their agency standards. NFPA 130 includes fire resistance of tunnel structures and materials, fire detection systems, firefighting points, emergency communication and train control, evacuation facilities and walkways, electrical supply, electrical wiring and installations, security, emergency ventilation, and emergency response plans. A list of these topics is shown in Table 6-4.

Table 6-4 *Documents That Address Supporting Systems of Rail Transit Tunnels*

Main Topic	Documents	Applicability
Fire Detection, Firefighting, and Fire Resistance	NFPA 130 Section 6.2 – Fire Resistance of Tunnel Structures and Materials	Codes/standards and guidelines fully applicable.
Fire Detection, Firefighting, and Fire Resistance	NFPA 130 Section 6.4.4 – Fire Detection	Codes/standards and guidelines fully applicable.
Fire Detection, Firefighting, and Fire Resistance	NFPA 130 Section 6.4.5 – Firefighting Points	Codes/standards and guidelines fully applicable.
Fire Detection, Firefighting, and Fire Resistance	NCHRP Report 836 Section 5 – Fixed Firefighting Systems	Supplementary Standards and Guidelines
Electrical System	NFPA 130 Section 6.4.8 – Electrical Supply	Codes/standards and guidelines fully applicable.
Emergency Systems	NFPA 130 Section 10 – Emergency Communication and Train Control	Codes/standards and guidelines fully applicable.
Emergency Systems – Ventilation	NCHRP Report 836 Section 3 – Tunnel Emergency Ventilation and Smoke Control	Supplementary standards and guidelines.
Security Systems	APTA – Tunnel Security for Public Transit	Supplementary standards and guidelines.

While NFPA 130 covers the relevant topics in rail transit tunnel supporting system design, additional supplementary material that expands upon the NFPA 130 standards may be helpful for agencies. For emergency ventilation, NCHRP Report 836 (2016)[110] on roadway emergency ventilation best practices could be adapted for rail transit tunnel designs. For security, APTA's *Tunnel Security for Public Transit* (2015) or TCRP Report 86/NCHRP Report 525 (2006) on tunnel security could be updated. The APTA guidelines primarily list the various security threats and mitigation techniques but do not detail how the technologies could be implemented. The TCRP Report 86/NCHRP Report 525[111] guidelines could be updated to reflect recent innovations in tunnel security systems.

Inspection and Maintenance

Railway tunnel inspection and maintenance focus on maintaining tunnel serviceability over the lifespan of the tunnel. No standards exist specifically for rail transit tunnel inspection, but a few best practice reports could be used to formulate recommended practices or standards (Table 6-5). The FHWA/FTA *Highway and Rail Transit Tunnel Inspection Manual* and the *TOMIE Manual* provide guidelines for road tunnel operation, maintenance, inspection, and evaluation that can be adopted for rail transit use. SRT TSI Section 4.5 covers maintenance rules for railway tunnels. The *AREMA Manual for Railway Engineering* (Chapter 1.8) specifies potential defects in the tunnel and the

---

[110] NCHRP Report 836, *op. cit.*

[111] TCRP/NCHRP, *Making Transportation Tunnels Safe and Secure*, TCRP Report 86/NCHRP Report 525, Volume 12, Transportation Research Board, 2006.

AREMA Bridge Inspection Handbook (Chapter 11 – Tunnel Inspection) provides a tunnel inspection checklist.

FHWA developed the *Specifications for the National Tunnel Inventory* (SNTI)[112] to help safeguard tunnels and to ensure reliable service levels on all public roads. The SNTI contains instructions for submitting the inventory and inspection data to FHWA, which will be maintained in the NTI database to track tunnel conditions throughout the United States. It is recommended to follow the FHWA standard of NTI for rail transit tunnels. A similar approach could be adopted for FTA's Transit Asset Management system.

Table 6-5 *Documents for Maintenance and Inspection of Rail Transit Tunnels*

Main Topic	Documents	Applicability
Inspection	*AREMA Bridge Inspection Handbook*, Chapter 11 – Tunnel Inspection	Codes/standards and guidelines fully applicable.
Inspection	FHWA/FTA *Highway and Rail Transit Tunnel Inspection Manual*	Codes/standards and guidelines fully applicable.
Inspection	*TOMIE Manual*	Supplementary standards and guidelines.
Maintenance	*AREMA Manual for Railway Engineering*, Chapter 1.8	Codes/standards and guidelines fully applicable.
Maintenance	SRT TSI, Section 4.5	Codes/standards and guidelines fully applicable.
Inventory	*Specifications for the National Tunnel Inventory*	Supplementary standards and guidelines.

Rehabilitation

Tunnel rehabilitation is performed to ensure proper serviceability, upgrade tunnels to meet higher specifications, and repair unacceptable tunnel performance and conditions.

Like inspection procedures, no industry standards are available for rail transit tunnel rehabilitation. FHWA's *Technical Manual for Design and Construction of Road Tunnels – Civil Elements* is the only document with guidelines about tunnel rehabilitation, including many methods of structural repairs for concrete, lining, steel, and masonry. Despite focusing on road tunnels, the FHWA document would be a good foundation for developing rail transit standards or guidelines.

Summary

A summary of standards and guidelines for all the topics discussed is shown in Table 6-6. It lists currently available standards and guidelines that rail transit agencies and construction companies could adopt for design, construction, support system elements, inspection and maintenance, and rehabilitation of transit tunnels.

---

[112] FHWA-HIF-15-006, *op. cit*.

Table 6-6 *Documents That Can Be Adopted for Rail Transit Tunnel*

General Topics	Codes/ Standards Available	Recommendations/ Guidelines Available	Comments
Structural Design	AASHTO LRFD	N/A	Standard is ready to be implemented but has missing aspects related to rail operation.
Construction	AASHTO LRFD	N/A	Standard is ready to be implemented but more construction methods could be included.
Supporting System Design	NFPA 130	N/A	Standard is ready to be implemented.
Supporting System Design	N/A	Ventilation: NCHRP 836 (2016)	The report provides relevant information but could be updated to reflect rail transit tunnels.
Supporting System Design	N/A	Security: APTA (2015) & TCRP Report 86/ NCHRP Report 525	The APTA guidelines list security technology that could be used to mitigate various threats but do not provide details about implementation. The NCHRP 525 guidelines could be updated to reflect recent security innovations.
Inspection and Maintenance	N/A	FHWA/FTA *Highway and Rail Transit Tunnel Inspection Manual* (2005); FHWA-HIF-15-005, *TOMIE Manual* (2015)	Standards are not available for inspection and maintenance. FHWA guidelines are ready to be implemented.
Inspection and Maintenance	N/A	*AREMA Bridge Inspection Handbook*, Chapter 11 – Tunnel Inspection	It is recommended to follow the FWHA *Specifications for the National Tunnel Inventory* (SNTI) standard for rail tunnels.
Rehabilitation	N/A	FHWA-NHI-10-034 *Technical Manual for Design and Construction of Road Tunnels – Civil Elements* (2009)	Standards are not available for rehabilitation. The FHWA guideline is ready to be implemented but more could be extended to address issues in aging rail tunnels.

Section 7

Conclusions and Findings

The following conclusions are based on the review of the industry requirements, literature review, data collection analysis, site visits, and resultant gap analysis.

- Regulations for fire safety and passenger evacuation were made a priority in the United States after the WMATA smoke incident in 2015 and multiple road tunnel fires in Europe between 1999 and 2001. Three recent NTSB recommendations for FTA related to rail transit tunnels are:
  - R-15-7: Audit all rail transit agencies that have subway tunnel environments to (1) assess the state of repair of tunnel ventilation systems, (2) assess written emergency procedures for fire and smoke events, (3) assess training programs to ensure compliance with these procedures, and (4) verify that rail transit agencies apply industry best standards, such as the National Fire Protection Association (NFPA) 130 *Standard for Fixed Guideway Transit and Passenger Rail Systems*[113] in maintenance procedures and emergency procedures.
  - R-16-01: Issue regulatory standards for tunnel infrastructure inspection, maintenance, and repair, incorporating applicable industry consensus standards into those standards.
  - R-16-02: Issue regulatory standards for emergency egress in tunnel environments.
- In the United States, there are 102 rail transit tunnels owned by 17 public transportation agencies. Of these tunnels, half are more than 50 years old, suggesting an aging infrastructure and potential difficulty in retrofitting with the current best supporting system practices.
- AASHTO's *LRFD Road Tunnel Design and Construction Guide Specifications* is the most comprehensive structural design document that can be adapted for rail transit tunnel structural design and construction.
- NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems provides standards mostly for supporting system design.
- Modifications of the *Recommended AASHTO Guidelines for Emergency Ventilation Smoke Control in Roadway Tunnels* (2016) to focus on rail transit tunnels would be a beneficial supplement to NFPA 130 for supporting system design.
- A handbook of best tunnel security practices could be based on APTA's *Tunnel Security for Public Transit* (2015) and TCRP Report 86/NCHRP Report 525 (2006).
- Site visits and agency queries noted tunnel inspection and rehabilitation are not standardized, but best practices could be based on the TOMIE Manual and FHWA NHI-10-034 Manual. Practices of rail transit agencies may

---

[113] NFPA 130, *op. cit.*

need to be further reviewed and results incorporated into an industry-wide best practices handbook.

- Investments in new tunnel construction technologies and comparisons of existing technologies for waterproofing and tunnel flooding would benefit agencies.
- Technologies for trespasser detection are rapidly advancing, and a guidebook of best practices would be beneficial.

Based on the results of the research and the feedback and suggestions of CUTR's Transit Safety Standards Working Group, the following findings are provided for industry consideration.

- Finding 1: Transit agencies should be aware of current and future research that compares AASHTO LRFD Road Tunnel Design and allowable stress design (ASD) method for new tunnel designs.
  - Data collection results show that transit agencies currently use a variety of standards. Five transit agencies have their own standards for design and construction, but there are another 12 transit agencies that do not have their own standards.
  - AASHTO's *LRFD Road Tunnel Design and Construction Guide Specifications* (2017) gives minimum requirements to design a tunnel that will last 150 years. However, the AASHTO guide is relatively new, so there have not been many projects completed since its release. More research should be conducted to make an analytical comparison between these two methods.
  - Future research should compare transit agency standards for rail tunnel design and construction with the new edition of AASHTO LRFD specifications.
- Finding 2: Transit agencies may consider implementing the latest version of NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems as a minimum requirement for new rail transit tunnels. Infrastructure topics include exits and technical rooms, fire resistance of tunnel structures, fire reaction of building materials, fire detection, evacuation facilities and escape walkways, firefighting points, emergency communication and train control, and emergency ventilation.
  - For existing tunnels, the retrofit and rehabilitation of existing rail transit tunnels should also satisfy NFPA 130 requirements, if possible.
  - This may potentially satisfy NTSB recommendations R-15-7 Part 4 and R-16-02.

- Finding 3: Transit agencies should be aware of guidelines or best practices for emergency ventilation developed by Standards Development Organization (SDOs), such as NCHRP 836, *Guidelines for Emergency Ventilation Smoke Control in Roadway Tunnels*.
    - A gap analysis indicates that available industry standards do not have details about emergency ventilation. NFPA 130 covers the basics of ventilation but does not have details on the best practices and how to implement them.
- Finding 4: Transit agencies should be aware of the many guidelines being developed for tunnel inspection, maintenance, and rehabilitation based on the *Highway and Rail Transit Tunnel Inspection Manual* and other available SDO sources. Guidelines particularly covering the following:
    - Minimum inspection frequency.
    - Condition-based rating standard for tunnels to help estimate when a tunnel requires emergent or long-term repair or rehabilitation.
        - Primary structural rehabilitation purpose – to restore structural elements to a state of good repair and to protect against future deterioration.
- Finding 5: Transit agencies may consider creating an industry working group to exchange knowledge about tunneling systems identified in Findings 1 thru 5.
    - Agencies visited under this project expressed interest in providing a method for communication and sharing of information among agencies with tunnels.

Appendix A Data Collection Form

Appendix A – Data Collection Form

Appendix A presents the data collection form sent out to the various rail transit agencies in the U.S. The sheet is displayed below:

Newly-Constructed and Older Tunnels Data

Transportation Technology Center, Inc. (TTCI) with support from the Center for Urban Transportation Research (CUTR) at the University of South Florida (USF) was tasked by the Federal Transit Administration (FTA) in researching standards for designing new rail tunnels, guidelines on assessing existing tunnel structures, and standards for rehabilitating older tunnel structures. As part of this effort, TTCI is collecting data from the transit industry on rail tunnels used or owned by agencies. The FTA has provided TTCI with a list of SSOA program managers (through TSO) to contact about helping TTCI obtain Rail Transit Agency's (RTA's) contacts that could help with this data collection effort. **Please complete a form for each individual tunnel in your agency system.**

If technical specifications can be provided in addition to the answers to the questions, please send them to anna_rakoczy@aar.com.

1. Agency Name: _____

2. Rail Mode(s) of operation (check all applicable):
   - Commuter rail service
   - Heavy rail service
   - Light rail service
   - Streetcar service
   - Other_____

3. Does your agency own or operate through railway transit tunnel(s) or have plans to own or operate through railway transit tunnels in the future? (Yes/No) _____

   a. If yes, where is the tunnel(s) located? _____
   b. What year was the tunnel(s) built or plan to be completed? _____
   c. Has the tunnel(s) been through a rehabilitation? If so, when? _____
   d. Please provide the following information on the types of tunnels you own: year built (or estimated completion year), shape, construction method, liner, finish, and any other specific information (select all applicable).

      Estimated Completion Year: _____

      Shape:
      - Circular
      - Horseshoe
      - Single-box

- Double-Box
- Oval
- Other_____

Construction method:

- Cut and Cover
- Shield Driven
- Bored
- Drill and Blast
- Immersed Tube
- Sequential Excavation Method
- Jacked Tunnel
- Other_____

Liner:

- Unlined
- Rock Reinforced (e.g., rock bolts)
- Shotcrete
- Ribbed systems
- Segmental
- Poured concrete
- Slurry Walls
- Other_____

Finish:

- Ceramic
- Porcelain-Enameled Metal
- Epoxy-Coated Concrete
- Coated Cementboard
- Precast Concrete
- Metal
- Other_____

Any other specific information that are applicable: _____

e. Does the tunnel have a risk assessment plan? If yes, please provide the standard(s) that was used to develop the risk assessment plan. ____

f. Which technical standards/specifications/guidelines are used for inspection (select all applicable)? If multiple standards are used, please list which standards are used for each specific aspects of inspection.
   - FHWA/FTA Highway and Rail Transit Inspection Manual
   - TOMIE Manual
   - Other_____

g. Which technical standards/specifications/guidelines are used for maintenance (select all applicable)? If multiple standards are used, please list which standards are used for each specific aspects of maintenance.
    - FHWA/FTA Highway and Rail Transit Tunnel Maintenance and rehabilitation
    - TOMIE Manual
    - Other_____

4. Has your agency designed a new tunnel in the past 10 years, or currently designing a new tunnel? (Yes/No) _____
    a. If yes, please provide the type of tunnel (shape, construction method, liner, finish, and any other specific information) (select all applicable).

        Shape:
        - Circular
        - Horseshoe
        - Single-box
        - Double-Box
        - Oval
        - Other_____

        Construction method:
        - Cut and Cover
        - Shield Driven
        - Bored
        - Drill and Blast
        - Immersed Tube
        - Sequential Excavation Method
        - Jacked Tunnel
        - Other_____

        Liner:
        - Unlined
        - Rock Reinforced (e.g., rock bolts)
        - Shotcrete
        - Ribbed systems
        - Segmental
        - Poured concrete
        - Slurry Walls
        - Other_____

        Finish:
        - Ceramic
        - Porcelain-Enameled Metal
        - Epoxy-Coated Concrete
        - Coated Cementboard
        - Precast Concrete

    - Metal
    - Other_____

   Any other specific information that are applicable: _____

   b. If yes, which technical standards/specifications/guidelines were used for the structural design (i.e., planning process, geotechnical investigation, permanent lining, construction methods, etc.) (select all applicable)? If multiple technical standards/specifications/guidelines were used, please list which standards were used for each specific aspect of the structural design.
      - AREMA Manuals
      - USDOT – FHWA Manuals
      - ACI Manuals
      - AISC Manuals
      - Agency Standards_____
      - Other_____

   c. Which technical standards/specifications/guidelines were used to design supporting systems (i.e., communication system, smoke and ventilation system, security system, etc.) (select all applicable). If multiple standards were used, please list which standards are used for specific aspects of the supporting system design.
      - AREMA Manuals
      - USDOT – FHWA Manuals
      - ACI Manuals
      - AISC Manuals
      - Agency Standards_____
      - Other_____

   d. If yes, are there any design/technical/other aspects that were not covered by any standards? If so, please list them. _____

5. Does your agency inspect existing railway tunnels? (Yes/No) _____
   a. If yes, please provide the age, location, and type of tunnels.
      Age: _____
      Location: _____
      Condition: _____
      Use numerically-based system for evaluating transit asset conditions: 5 (excellent), 4 (good), 3 (adequate), 2 (marginal), 1 (poor)
      Shape:
      - Circular
      - Horseshoe
      - Single-box
      - Double-Box
      - Oval
      - Other_____

Construction method:

- Cut and Cover
- Shield Driven
- Bored
- Drill and Blast
- Immersed Tube
- Sequential Excavation Method
- Jacked Tunnel
- Other_____

Liner:

- Unlined
- Rock Reinforced (e.g., rock bolts)
- Shotcrete
- Ribbed systems
- Segmental
- Poured concrete
- Slurry Walls
- Other_____

Finish:

- Ceramic
- Porcelain-Enameled Metal
- Epoxy-Coated Concrete
- Coated Cementboard
- Precast Concrete
- Metal
- Other_____

Any other specific information that are applicable: _____

b. If yes, what is the frequency of tunnel inspections? _____

c. If yes, which technical standards/specifications/guidelines are used for inspection (select all applicable)? If multiple standards are used, please list which standards are used for each specific aspect of inspection.
    - FHWA/FTA Highway and Rail Transit Inspection Manual
    - TOMIE Manual
    - Other_____

d. If yes, which technical standards/specifications/guidelines are used for repair (select all applicable)? If multiple standards are used, please list which standards are used for each specific aspect of repair.
    - FHWA/FTA Highway and Rail Transit Tunnel Maintenance and rehabilitation
    - TOMIE Manual
    - Other_____

6. Has your agency rehabilitated an older tunnel in the past 10 years? (Yes/No) _____
    a. If yes, please provide the age, location, and type of tunnel.
       Age: _____
       Location: _____

       Shape:
        - Circular
        - Horseshoe
        - Single-box
        - Double-Box
        - Oval
        - Other_____

       Construction method:
        - Cut and Cover
        - Shield Driven
        - Bored
        - Drill and Blast
        - Immersed Tube
        - Sequential Excavation Method
        - Jacked Tunnel
        - Other_____

       Liner:
        - Unlined
        - Rock Reinforced (e.g., rock bolts)
        - Shotcrete
        - Ribbed systems
        - Segmental
        - Poured concrete
        - Slurry Walls
        - Other_____

       Finish:
        - Ceramic
        - Porcelain-Enameled Metal
        - Epoxy-Coated Concrete
        - Coated Cementboard
        - Precast Concrete
        - Metal
        - Other_____

       Any other specific information that are applicable: _____

b. Which technical standards/specifications/guidelines are used for evaluation of older tunnels (select all applicable)? If multiple standards are used, please list which standards are used for each specific aspect of evaluation.
    - FHWA/FTA Highway and Rail Transit Inspection Manual
    - TOMIE Manual
    - Other_____

c. Which technical standards/specifications/guidelines were used for rehabilitation (select all applicable)? If multiple standards were used, please list which standards were used for each specific aspect of rehabilitation.
    - FHWA/FTA Highway and Rail Transit Tunnel Maintenance and rehabilitation
    - TOMIE Manual
    - Other_____

Please provide contact information in case TTCI has any technical questions regarding the specifications:

Name: _____
Phone: _____
Email: _____

Appendix B

Fire Curves

Appendix B briefly describes various fire curves that are referenced under "Fire Resistance of Tunnel Structures" in Section 3. The two curves, Rijkswaterstaat (RWS) and EUREKA (RABT ZTV) curves, were developed in Europe to predict the temperature within a confined space after a car or train catches on fire. The RABT ZTV curves were developed from the Eureka project in Germany and have both a car and train version. The RWS curves were developed in the Netherlands by the Rijkswaterstaat Ministry of Transport and simulate an oil tanker fire.

A comparison of the curves is illustrated in Figure B-1. While the maximum temperature is relatively similar, the RWS curve has a greater temperature for an extended period of time, whereas the RABT ZTV curves drop off at a quicker rate.

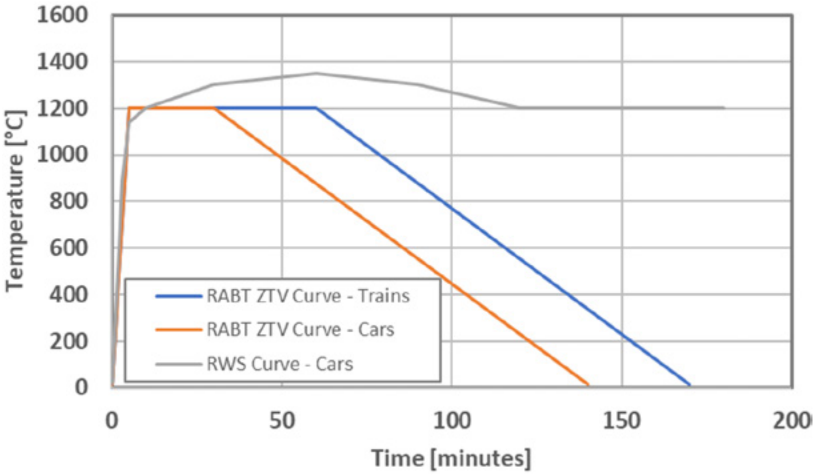


Figure B-1 *Various fire temperature curves*

U.S. Department of Transportation
Federal Transit Administration

U.S. Department of Transportation
Federal Transit Administration
East Building
1200 New Jersey Avenue, SE
Washington, DC 20590
https://www.transit.dot.gov/about/research-innovation