FTA Report No. 0236

FTA RESEARCH
FEDERAL TRANSIT ADMINISTRATION

Research Report and Findings: Specifications and Guidelines for Rail Tunnel Inspection and Maintenance

PREPARED BY
Anna Rakoczy
Colin Basye
Dingqing Li
Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads

NOVEMBER 2022

U.S. Department of Transportation
Federal Transit Administration

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55500 DOT Road
Pueblo, CO 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

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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)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE November 2022	2. REPORT TYPE Final		3. DATES COVERED 2016–2017
4. TITLE AND SUBTITLE Review of Specifications and Guidelines for Rail Tunnel Inspection and Maintenance			5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Anna Rakoczy, Colin Basye, Dinqing Li			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. 0236
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/10.21949/1527649] Suggested citation: Federal Transit Administration. Review of Specifications and Guidelines for Rail Tunnel Inspection and Maintenance. Washington, D.C.: United States Department of Transportation, 2022. https://doi.org/10.21949/1527649.			
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15. SUBJECT TERMS Rail transit tunnel, tunnel structures, inspection, maintenance, 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	105	19b. TELEPHONE NUMBER

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

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Abstract

To effectively respond to recommendations of the National Transit Safety Board (NTSB), FTA contracted with researchers to assist the transit industry in developing standards and/or recommended practices for tunnel inspection and maintenance, repair/rehabilitation, and emergency egress. This report summarizes current industry maintenance and inspection practices based on data collected and compiled in 2017 and identifies and describes new technologies for groundwater intrusion remedies, inspection tools, and structural health monitoring. A literature review covers inspection requirements, frequency, techniques, and documentation as well as tunnel condition rating criteria. Findings based on standard comparisons, guideline assessments, and working group discussions are presented.

Executive Summary

Background

The Federal Transit Administration (FTA) entered into a Cooperative Agreement with the Center for Urban Transportation Research (CUTR) at the University of South Florida to research areas of transit safety risk, identify existing standards and recommended practices to address those areas of risk, 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. At the direction of FTA, CUTR and its research partner, the Transportation Technology Center, Inc. (TTCI), are performing research and background studies on various topics to collect the information necessary for FTA to issue recommendations to the industry on voluntary standards or publish guidance documents or resource reports to assist the industry in mitigating areas of risk. This report is focused on specifications and guidelines for rail transit tunnel maintenance, inspection, repair, and rehabilitation.

Context

After a Washington Metropolitan Area Transit Authority (WMATA) L'Enfant Station accident in 2015, in which electric arcing of a circuit due to prolonged moisture from tunnel leakage caused a passenger train to stop in the smoke-filled tunnel resulting in a passenger fatality, the National Transportation Surface Board (NTSB) issued two recommendations directed at FTA. Delays in evacuations from the passenger train in the tunnel were caused by the smoke in the tunnel, failed ventilation fan components, and delayed emergency egress under less-than-desirable conditions (lighting and walkways). The two recommendations were:

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

To effectively respond to NTSB's recommendations, FTA contracted with a research team consisting of CUTR and TTCI personnel to assist the transit industry in developing standards and/or recommended practices for tunnel inspection and maintenance, repair/rehabilitation, and emergency egress. Project objectives include three focus areas:

- *Improved tunnel inspections and maintenance* by exploring new and existing technologies for inspection elements.

- *Tunnel repairs and rehabilitation*, including a condition-based rating system for tunnels as a tool for evaluation for rehabilitation and guidelines for a tunnel inventory database.
- *Standards or guidelines* that should be used for planning emergency egress from tunnels.

This report covers tasks related to tunnel inspections and maintenance and includes:

- A literature review summarizing and comparing current specifications and standards for rail transit and highway tunnel inspection and maintenance in the U.S.
- Identification of existing and emerging tunnel inspection technologies.
- Research and findings for developing standards, protocols, guidelines, or recommended practices associated with rail tunnel inspections and maintenance and to support the American Public Transportation Association (APTA) as needed for standard/recommended practice development.

Methods

The inspection and maintenance information reflected in this report was gathered primarily through a literature review and previous research completed for FTA in 2017 that identified gaps in available standards and guidelines related to railway tunnel inspection.

The first section summarizes current industry maintenance and inspection practices. Of the 37 transit agencies surveyed, 17 indicated using at least one rail tunnel. Five transit agencies were selected for site visits to discuss current practices related to inspection of existing track and wayside structures. This included tunnel inspection and maintenance challenges imposed by aging structures and years of environmental effects. In general, it was observed that transit agencies with tunnels had a wide range of practices regarding tunnel design, inspection, and maintenance. About half of the tunnels were built over 50 years ago, and about 15% were built over 100 years ago. As of 2017, only about 20% of U.S. rail transit tunnels had been fully or partially rehabilitated since their original construction.

The second section identifies and describes new technologies for groundwater intrusion remedies, inspection tools, and structural health monitoring. Some new inspection and repair technologies have not been used by agencies and are potential solutions. Agencies indicated that future work and testing might be needed to evaluate the application of these emerging repair and environmental mitigation technologies.

A review of the available standards for tunnel inspection and maintenance is presented, including inspection requirements, inspection frequency, inspection techniques, documentation, and tunnel condition rating criteria. Sources include the *Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual*[1] and the *Specifications for National Tunnel Inventory* (SNTI).[2] Other tunnel and maintenance references include APTA RT-FS-S-001-02, SRT TSI 4.5, NCHRP Project 20-07 (Task 261 and Task 276), the *AREMA Manual*, and the *AREMA Bridge Inspection Handbook.*

Key Findings

Findings were based on standard comparisons, guideline assessments, and working group discussions and include the following:

- The SNTI and the TOMIE manuals were the most comprehensive documents for tunnel maintenance and inspection. Transit agency inspection procedures could be aligned with the criteria and techniques described therein.
- FTA's tunnel structural component rating system could be refined to use elements of the SNTI rating system. FTA uses a five-point scale, and the SNTI uses a four-point scale and defines conditions for each tunnel element/component.
- FTA may consider developing a standard or recommendation through the rulemaking process that would become a part of the Transit Asset Management (TAM) requirement for rail tunnel inventory, similar to FHWA's National Tunnel Inventory (NTI) database of highway tunnels.
- Investments in new technologies and comparisons of existing technologies for waterproofing, groundwater intrusion mitigation, and tunnel inspection tools are beneficial to agencies. Future research on application, demonstration, and testing under certain conditions is necessary to evaluate the full benefits of these technologies for transit tunnels.

[1] Federal Highway Administration (2015), FHWA-HIF-15-005, *Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual*, Washington DC.

[2] Federal Highway Administration, FHWA-HIF-15-006, "Specifications for National Tunnel Inventory," 2015, http://www.fhwa.dot.gov/bridge/inspection/tunnel/.

Section 1

Introduction

Railroad tunnels are an integral part of the rail transit industry and are critical for the movement of passengers across cities in the U.S. However, the existing tunnel infrastructure inventory consists of many tunnels exceeding 100 years of age and represents potential chokepoints that can severely disrupt passenger mobility during fire, structural, or security incidents. Tunnels also represent significant financial investments with challenging design, construction, and operational issues.

Life expectancies of tunnel infrastructure are significantly longer than those of track components or supporting systems. Therefore, special attention needs to be dedicated to long-term tunnel inspection and maintenance. Tunnel inspection requires multi-disciplinary personnel familiar with various functional aspects of a tunnel, including civil/structural, mechanical, electrical, drainage, and ventilation components, as well as some operational expertise with signals, communications, fire-life safety, and security. If an inspection reveals any issues within a tunnel structure or supporting systems, simple to more complex maintenance processes need to be performed. A tunnel will require complex retrofit upgrades or complete rehabilitation if large-scale repairs and upgrades are required.

U.S. transit agencies surveyed in 2017 identified operations requirements, including inspection and maintenance guidelines used for inspecting tunnel structure integrity and supporting systems. Additionally, agencies expressed interest in identifying new technologies that can be implemented to improve tunnel inspections and structural safety.

The Federal Transit Administration (FTA) sponsored this research to develop recommendations for the transit industry for the development of tunnel inspection, maintenance, repair, and rehabilitation standards and/or recommended practices. Further, development of a standardized tunnel emergency egress procedure is warranted.

A comparison of existing inspection and maintenance standards was completed and includes details of inspection procedures and methods, frequency of inspections, and components to be inspected. The comparison is presented, and findings are provided.

Section 2

Current Industry Practices

To better understand the tunnel practices and standards used for transit rail tunnels in the U.S., the Transportation Technology Center, Inc. (TTCI) conducted a 2017 data collection effort of U.S. transit agencies. Of the 37 transit agencies surveyed, 17 indicated they owned at least one tunnel. The purpose of the data collection and specific data were presented in a previous TTCI report (P-18-008).[3] This document presents highlights from that survey.

In addition to the survey, five transit agencies were selected to visit and discuss their current practices for new tunnel design and inspection and maintenance of existing tunnels. Details of the site visits are presented in the report (P-18-008) cited above. This section summarizes current practices related to tunnel inspections, maintenance, and challenges of aging structures. Previous research identified gaps in available standards and guidelines related to railway tunnel inspection. Transit agencies expressed interest in developing standard(s) or guideline(s) that could be used across the industry.

Statistics

Results of the data collection survey provided insight into the practices of various rail transit agencies regarding tunnel design, inspection, and maintenance. General remarks from the results analysis include the following:

- Results showed a wide range of tunnel construction dates, with three tunnels built in the 1800s and six currently under construction. In the U.S., there were 102 rail transit tunnels owned by 17 public transportation agencies. Of these, half are over 50 years old, suggesting an aging infrastructure and potential difficulty in retrofitting the current best supporting system practices (Figure 2-1).
- Older tunnel infrastructure was not designed to incorporate recent advances in supporting systems such as ventilation ports and firefighting access points. These advances in tunnel design have gradually improved over the past few decades.
- Although tunnels are aging, only 20% of the U.S. rail transit original tunnels constructed have been fully or even partially rehabilitated.
- Transit agencies have a wide range of design, inspection, and maintenance practices.
- Inspection frequency can vary from weekly to every six years; about half of transit agencies inspect their tunnels within a 1-3-year time range (9 out of 17).

[3] Rakoczy, A. M., Wilk S., Jones M. C.,“Review of Specifications and Guidelines for Rail Tunnel Design, Construction, Maintenance, and Rehabilitation,” TTCI, P-18-008, November 2017.

- Many transit agencies use design, inspection, and maintenance manuals developed for highway tunnels. The three most commonly used manuals and standards for tunnel inspections are the *FHWA/FTA Manual*;[4] the *Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual*;[5] and rail agency standards. The manual most commonly used for maintenance and rehabilitation is the *FHWA/FTA Road and Rail Tunnel Maintenance and Rehabilitation Manual.*
- Transit agencies with multiple tunnels tend to have their own agency standards. It is unclear how these standards compare and the general guidelines published by FHWA or FTA.

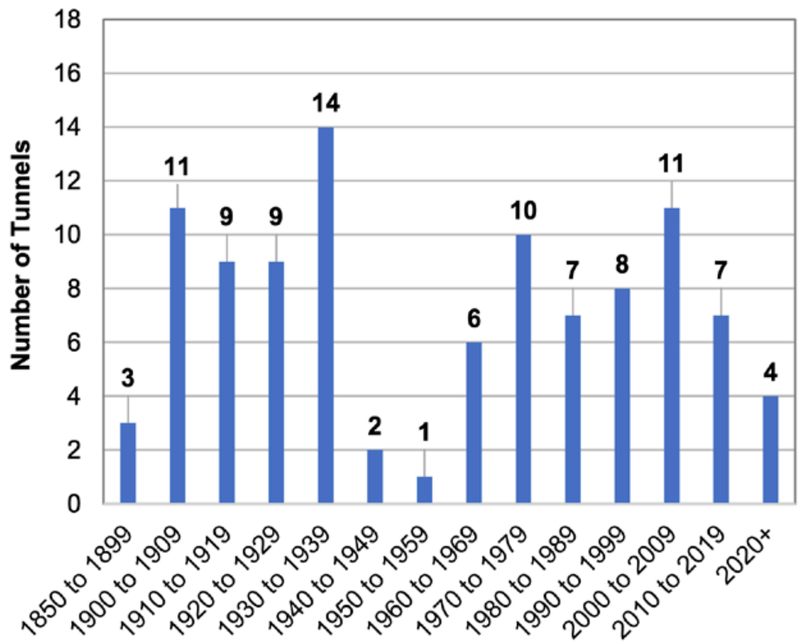


Figure 2-1 *Year of Construction of Rail Transit Tunnels in U.S.*

Tunnel Inspection Practices

An ongoing challenge of inspection and maintenance is that tunnels must remain in service. As a result, inspection and maintenance activities have limited maintenance time windows and usually must be completed at night, which restrains the time and capabilities for large-scale projects and applies to all transit tunnels.

[4] FHWA/FTA, FHWA/FTA 2005, *Highway and Rail Tunnel Inspection Manual*, Washington, DC, 2005.
[5] FHWA-HIF-15-005, *op. cit.*

Inspection Type and Frequency

The frequency of tunnel inspections varies, but the most common frequency noted from site visits is 1–3-year intervals. Inspection of tunnel structures is often at night during non-revenue hours. Several departments inspect different aspects of a tunnel, such as lighting, track, track drainage, traction power, and signals.

Inspection types used in transit tunnels include the following:

- Visual inspections, typically performed on foot
- Special inspections performed using ground-penetrating radar (GPR) and laser scans, but only in some locations, as new technologies are cost-prohibitive. (*Note*: GPR and infrared scanning techniques are used to locate voids and trapped water in tunnel liners.)
- Ultrasonic inspections
- Electromagnetic inspection of steel components
- Inspection of pumps for condition and proper operation
- Inspection and operational checks of upper gallery exhaust dampers (monthly)
- Track geometry inspections

Inspection Findings

- The most common inspection finding is groundwater intrusion due to leakage, especially in older tunnels constructed without waterproofing membranes or because the membranes deteriorated. Leakage may create electrical issues and component deterioration due to corrosion.
- Leakage is difficult to eliminate if the tunneling system is located below the water table. This brings complications such as accelerated corrosion and deteriorated concrete.
- Exposure to salty water during surface street flooding or from surface street water penetrating through ventilation shafts is difficult to mitigate. Even if a concrete crack is repaired, the salt retained (backlog) in the small cracks will lead to accelerated corrosion and concrete deterioration.
- Corrosion of steel components – often, deterioration is more visible near ventilator equipment banks
- Rusty pumps, missing bolts, concrete spalling
- Brake dust and trash collection, as both can lead to a fire in a tunnel

Supporting Systems

Different departments are responsible for inspecting and maintaining supporting systems—the power department for cable inspection, the signal department for communication and signals, railroad engineers for track inspection, and external companies for ventilation, drainage, and pump stations.

- The interval of inspection depends on system requirements.
- The most common issue for tunnel supporting systems is water intrusion from stations and emergency exits.
- The communications maintenance in tunnels includes Emergency Alarm/ Emergency Telephone (EA/ET) and under-river tube Security Systems (CCTV, intercoms, access intrusion control, and laser intrusion detection).
- Tunnel supporting systems that need to be retrofitted or rehabilitated include fiber optics, radiating antenna/radio systems, telephone cabling, and EA/ET.

Lessons Learned and Recommendations for Future Projects

- New design and construction tunnels should be waterproof.
- New design should consider how to inspect and maintain the structure.
- Clearance should be bigger for utility structures and maintenance purposes.
- Standards and regulations should be technically feasible and reasonably accomplishable.
- A list of materials available for use during a repair should be available along with their application protocols, which will help facilitate decision(s) about the repair method.
- Corrosion is evident where surface ventilators allow entry of water (runoff) laden with winter de-icing 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.
- 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, including facilities for installing active, powered communication equipment.
- WMATA recommends new tunnel design to ensure redundancy of design structure and supporting systems.

Maintenance Practices

After each inspection, action items are considered for maintenance and repairs. Small and low-budget actions are considered maintenance items. Findings and associated action items that are complex usually require a larger budget and will be included in a larger-scale repair project.

The challenges for inspection and maintenance are related to the available time and clearance to proceed wayside. It is difficult to perform inspections in short time periods during non-revenue hours. For more complex projects, it is difficult to obtain track time. Tunnel clearance often is limited, especially in older tunnel structures, which were not designed with 3-ft-wide (0.9 m) walkways as required by current standards.

Typical Maintenance Actions

The most typical maintenance performed in tunnels is related to leak mitigation, injecting concrete cracks, patching spalled concrete, coating steel liners and components to protect them from corrosion, and replacing missing bolts and small corroded steel components. Other activities include:

- Regular track maintenance
- Cleaning out sumps
- Removing brake dust and debris
- Replacing light bulbs
- Cathodic protection (CP) to control the corrosion of metal surfaces in the tunnel
- Performing track inspection according to Federal Railroad Administration (FRA) standards

Section 3

New Technologies

Industry stakeholders are using technologies for tunnel inspections. A literature review of technologies being used is described in this section. Some technologies are already successfully used in transit tunnels, but descriptions are provided for other transit agencies that may not be aware of such technologies. Other new technologies for inspection techniques and repair methods may not have been used in tunnels yet but show potential; they also are presented in this section but future work and testing may be needed to evaluate the applicability of these technologies for transit tunnels.

Technologies to Mitigate Groundwater Intrusion

Groundwater intrusion can be mitigated by treating the soil or sediment outside the tunnel, placing a membrane curtain inside the tunnel, or sealing the inside of the tunnel. The selection of the proper repair product for the conditions found on a project is key to the success of a leak containment program. Each site has its own specific environmental and physical properties. The pH, hardness, chemical composition, and turbidity of the groundwater entering the tunnel all contribute to the ability of the chemical or particle grouts to seal the leaking condition effectively. The physical conditions that created the defect, crack or joint movement, the potential for freezing, and the amount of water inflow are site-specific constraints for selecting the repair material. All these parameters must be assessed. Ideally, if movement of the crack or joint is suspected, it is best to monitor the defect for a time to provide an estimate of actual movement.

The most common method of sealing leaking cracks and joints is to inject a chemical (Table 3-1) or particle grout (Table 3-2) directly into the crack or joint. 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 with grout. Grout selection depends on the groundwater inflow and chemical properties of the soil and water.

Table 3-1 *Typical Chemical Grouts for Leak Sealing*

Description	Viscosity	Toxicity	Strength	Remarks
Acrylamides	Low (10 cps 2:1)	High	Low	Flexible
Acrylates	Low (10 cps)	Low	High	Semi flexible; no shrinkage, good success record
Silicates	Low (6 cps)	Low	High	Non-flexible high-shrinkage
Lignosulfates	Low (8 cps)	High	Low	Flexible not widely used
Polyurethane (MDI)	High (400 cps)	Medium	Low	Flexible, good success record (hydrophilic)
Polyurethane (TDI)	High (400 cps)	Medium	Low	Flexible, good success record (hydrophobic)

Table 3-2 *Typical Particle Grouts for Leak Sealing*

Description	Viscosity	Toxicity	Strength	Remarks
Fly-ash Type F;C	Med (50 cps - 2:1)	Low	High	Non-flexible
Type I Cement	Med (50 cps - 2:1)	Low	High	Non-flexible
Type III Cement	Med (15 cps - 2:1)	Low	High	Non-flexible
Microfine Cement	Low (8 cps - 2:1)	Low	High	Non-flexible
Bentonite	Med (50 cps - 2:1)	Low	Low	Semi-flexible

Grout selection also depends on the width, moisture content, and potential for crack or joint movement:

- For joints that move, only chemical grout is appropriate. The joint or crack movement will fracture particle grout and cause the leak to reappear. Single-component water-reactive polyurethane chemical grout is the most effective grout for the full depth sealing of cracks and joints with moisture present.
- A hydrophilic grout should be used if the defect is subject to seasonal wetness and is dry at the time of repair. When using a hydrophilic grout, water must be introduced into the defect to catalyze the grout. Hydrophobic grouts have a catalyzing agent injected with the chemical grout or premixed into the grout prior to injection. In both cases, water or a catalyst is used to gel the grout. Alternatively, hydrophobic chemical grout may be used. Hydrophobic chemical grouts rely upon a chemical reaction to cure, whereas hydrophilic chemical grout requires water to catalyze. Common hydrophobic grouts are acrylates and closed-cell polyurethane. The installation of both types of grouts is similar to that described above.

- In situations in which the defect is not subject to movement and is dry at the time of repair, an epoxy grout can be injected into the defect in the same manner that concrete is structurally rebounded.
- Polyurethane sand acrylates are the most commonly used grouts for sealing cracks in tunnel liners.

Groundwater intrusion is one of the biggest problems for aging tunnels; new products to seal the leaks are now available. One novel solution is a product known as NOH2O. This product was successfully used on cast-iron rings in the Steinway Tunnel to stop minor leakage at ring segment joints and bolts. New York City Transit is using it as the current groundwater intrusion remedy in tunnels. NOH2O was designed for the sealing of water with a high-velocity washout rate, as well as high hydrostatic pressure. NOH2O is extremely impenetrable and, once coagulated, extremely flexible, resulting in more resistance to water leakage during future ground movement or shocks from blasting or excavation. This method has successfully sealed single leaks with flow rates of 2600 GPM and inflows with pressures of 2500 P.S.I.

NOH2O is injected into a water-bearing crack or fissure via a hole drilled intersecting the flow. A multi-port injector is inserted into the hole through which the NOH2O and/or additives are injected. More than one may be drilled for injection purposes. Generally, in situations in which the flow velocity is moderately low, NOH2O will be sufficiently activated by agitation alone, thus stopping the flow. In high flow situations, chemical activation may be required.

Although the addition of the activator results in NOH2O grout becoming unstable, followed by rapid coagulation, the addition of an inhibitor increases the stability, thereby reducing its tendency to coagulate when subjected to agitation. This enables the grout to penetrate greater distances through the formation before solidifying.

Inspection Tools

One of the challenges for inspection and maintenance is related to available time and clearance. Therefore, mobile inspection tools are in demand. Mobile mapping system inspection is based on high-definition image data and documents the condition of the infrastructure object with clarity. Changes that occur in the object are visualized with certainty in the innovative software with standardized visualization and phenomena catalogs. They include:

- Laser scanner – the newest generation allows the acquisition of > 1 million data points/second with millimeter accuracy.
- Inertial measurement system (IMU) – these high-end sensors allow precise measurements, even at high speeds (up to 80 km/h).

- Camera – calibrated multi-camera systems for image-supported surveying (e.g., airborne) or as a complement to laser scanning.
- GNSS – satellite-supported navigation for unmanned aircraft or precision referencing of measurement runs.

The latest technology can provide inspection plans with damage condition, create a damage report, and calculate the statistics.

Ground-Penetrating Radar (GPR)

GPR systems using high-frequency radar can detect underground utilities, particularly non-conductive pipes and ducts. When locating underground utilities, GPR can be a valuable complement to electromagnetic cable and pipe locators. GPR can be used for imaging the quality of concrete and reinforcements in tunnels, along with imaging void areas that can form at the concrete/earth interface.

Innovative GPR systems use ultra-wide band 250MHz, specifically chosen for effective utility-locating. GPR data collection can be done quickly at normal rail traffic speeds and the tunnel cleared for use immediately afterward. Data processing usually requires post-processing and office work.

GPR technology can help to locate rebar and post-tension cables within the concrete. Reinforcing steel locations are marked directly on the work surface to ensure safe and efficient drilling that will preserve the structure's integrity and reduce the need for repairs or patching. GPR scanning is useful to locate electrical outfitting, plumbing, fire protection services, drain installation, and duct work.

GPR technology can locate voids—air gaps between the sub-grade, dirt, and concrete slab-on-grade— hidden below concrete or asphalt surfaces. This degradation occurs over time due to compaction, pipe ruptures, or erosion but is often undetectable on the surface. GPR technology can help locate these areas and – most importantly – avoid collapses.

Ultrasonic and Electromagnetic Waves

The use of ultrasonic and electromagnetic waves is continuously increasing for nondestructive evaluation (NDE) and structural health monitoring (SHM) of civil, mechanical, electrical, biomedical, and aerospace structures and structural components. For NDE/SHM applications of various structural components, guided waves are becoming more popular, as these waves can propagate long distances and reach regions that are difficult to access otherwise. Ultrasonic waves are not harmful such as X-rays and are relatively easy to generate. An ultrasound impulse's travel time depends on material density, soundness, and other factors. As concrete degrades, its density and soundness change and are detectable using methods including ultrasound, so this may be an area that would warrant further exploration.

Ultrasonic waves can be used to estimate steel component thickness and percentage of corrosion in steel components and members such as tunnel's steel liners and ribs. The steel liner panels are usually 0.5-in. (12.7 mm) thick, and the steel ribs are 1-in. (25.4 mm) thick. Corrosion could start on the side that is not visible, making them difficult to inspect; therefore, an ultrasonic thickness measurement can help estimate the remaining sound steel thickness. This information will provide good value in evaluating structures for rehabilitation. This technology is used already to assist with load ratings of steel bridges or concrete-encased I-beams. However, current methods require a gel or contact medium between the ultrasound emitter, detector, and the target material. This slows the inspection process.

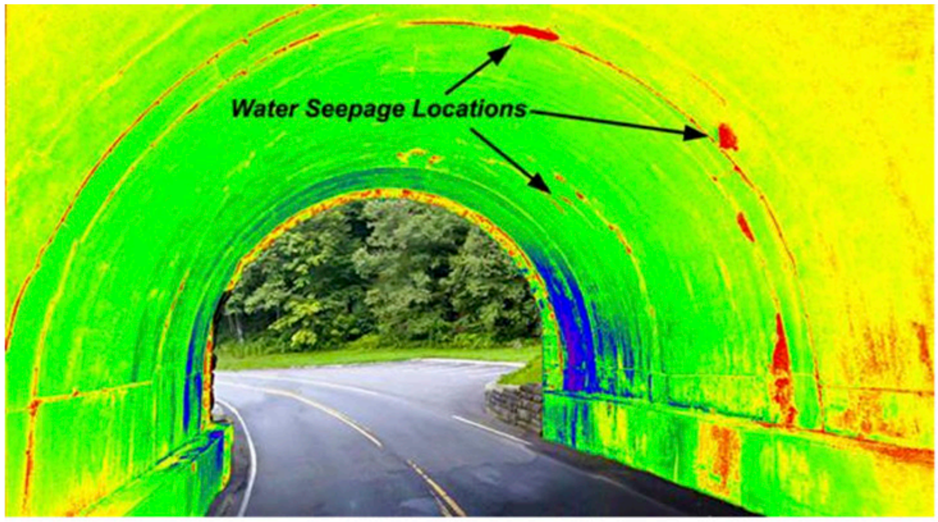
Ultrasonic waves cannot penetrate deep inside many porous materials. Terahertz (THz) frequency electromagnetic radiation has been found to be helpful in inspecting such materials. Recent advances in research related to NDE and SHM of various materials and structures using ultrasonic guided waves and THz electromagnetic radiation are available; however, further work is needed for transit tunnel application.

Infrared Imaging

Infrared imaging can be quick and produce basic information on where tunnel leaks occur based on temperature changes within the tunnel walls. In addition, this technology has been used successfully to identify areas where concrete delamination is happening, and water is seeping into the laminations.[6]

Infrared imaging is used in the tunnel, as shown in Figure 3-1, to identify water saturation or leakage areas. Wet materials exhibit an increase in reflectivity, making them appear hotter or colder than the same adjacent dry material.

[6] Washer, G., Dawson, J., Ruiz-Fabian, P., Sultan, A., and Trial, M., "Field Testing of Hand-Held Infrared Thermography, Phase II TPF-5(247)," Final Report for Missouri Department of Transportation, https://library.modot.mo.gov/RDT/reports/TRyy1144/cmr16-007_Final.pdf, 2016.



(Courtesy Veritas Material Consulting, Boise, ID)

Figure 3-1 *Tunnel Degradation and Infrared Tunnel Imaging*

Lidar Laser Scanning

Lidar (also called LIDAR, LiDAR, LADAR) is a surveying method that measures the distance to a target by illuminating the target with pulsed laser light and measuring the reflected pulses with a sensor. Differences in laser return times and wavelengths can then be used to make digital three-dimensional representations of the target. The name lidar, now used as an acronym for light detection and ranging (sometimes light imaging, detection, and ranging), was originally a combination (portmanteau) of light and radar. Lidar sometimes is called 3D laser scanning, a blend of 3D scanning and laser scanning, and has terrestrial, airborne, and mobile applications.

Lidar is becoming more widely used in the geotechnical community as its number of applications increases. It has been shown to be useful in tunnel inspections for applications such as rock mass characterization and discontinuity measurements, in addition to progressive deformation of soft bedrock and concrete panel displacement. Before a comprehensive methodology can be developed, the accuracy issues associated with scanning must be fully understood. This includes image resolution degradation caused by surface roughness effects in mapping, wavelength induced and subject color errors, laser spot diameter error, and atmospheric scattering caused by dust and humidity.[7]

[7] Delaloye et al., "Accuracy Issues Associated with Lidar Scanning for Tunnel Deformation Monitoring," 2011 Pan-Am CGS Geotechnical Conference.

Drone Technology

Drones have been used for various commercial projects and inspection tasks, including railway sections and bridges, and they appear to be good candidates for providing visual inspections and recordings of tunnel arches and accessible structural components. They can quickly approach an area of interest without ladders or bucket trucks, offer unimpeded traffic flow conditions during inspections, and take photos, videos, and other measurements of areas of interest, using one operator.[8]

Robots

A robot inspection system can autonomously navigate within a tunnel and record stereo images to identify defect types. It provides crack detection via deep learning computer algorithms. This is followed by a detailed 3D model of the cracked area using photogrammetric methods. Finally, a laser profiling of the tunnel's lining is obtained for a detail of the region close to the detected crack, identifying areas of potential deformation. More details about this technology can be found in an article by Protopapadakis et al. (2016).[9]

Structural Health Monitoring

Structural health monitoring (SHM) refers to implementing a damage detection and characterization strategy for engineering structures in real time and can be an alternative to periodic inspection. In SHM, damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity that adversely affect the system's performance. The SHM process involves observing a system over time using periodically sampled dynamic response measurements from an array of sensors, extracting damage-sensitive features from these measurements, and statistically analyzing these features to determine the current state of system health. For long-term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function, considering the inevitable aging and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide reliable information regarding the structure's integrity in near real-time.[10] Infrastructure inspection plays a key role in public safety regarding long-term damage accumulation and post extreme event scenarios. As part of the rapid developments in data-driven technologies transforming many fields

[8] "UAV Inspection of a Tunnel Under Construction," https://www.expouav.com/news/latest/using-drone-technology-construction-tunnel-environment/.

[9] Protopapadakis, E., et al. "Autonomous Robotic Inspection In Tunnels," Institute of Communication and Computer Systems, Zografou GR-157 80, Athens, Greece, 2016.

[10] Dawson, B., "Vibration Condition Monitoring Techniques for Rotating Machinery," *Shock and Vibration Digest*., 8(12), 3. doi:10.1177/058310247600801203, 2016.

in engineering and science, machine learning and computer vision techniques are increasingly capable of reliably diagnosing and classifying patterns in image data, which has clear applications in inspection contexts.[11]

[11] Davoudi, R., Miller, G., and Kutz, N., “Data-Driven Vision-Based Inspection for Reinforced Concrete Beams and Slabs: Quantitative Damage and Load Estimation," *Automation in Construction*, 96, 292–309, 2019. doi:10.1016/j.autcon.2018.09.024.

Section 4

Review of Available Standards and Guidelines for Tunnel Inspection and Maintenance

This section presents a literature review of existing U.S. and international standards, guidelines, and recommendations regarding transit tunnel inspection and maintenance. The objective is to outline the major elements required to develop one comprehensive document that can reference industry-accepted standards and guidelines for tunnel inspection and maintenance.

Previous research completed for FTA in 2017 identified gaps in available standards and guidelines related to railway tunnel inspection. Comprehensive inspection and maintenance standards for rail transit tunnels currently do not exist, but several manuals, handbooks, and specifications for highways can be used.

Inspection Requirements

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.

FHWA developed the National Tunnel Inspection Standards (NTIS),[12] the *TOMIE Manual*,[13] and the SNTI[14] to help safeguard tunnels and ensure reliable service levels on all public roads. The NTIS contains the regulatory requirements of the National Tunnel Inspection Program (NTIP); the *TOMIE Manual* and the SNTI have been incorporated by reference into the NTIS to expand upon the requirements.

The National Tunnel Inventory (NTI) database contains all the initial tunnel inventory and inspection data. This inventory of all highway tunnels subject to the NTIS, including the preliminary inventory information, reflects the findings of the most recent tunnel inspections conducted and is consistent and coordinated with the SNTI. The SNTI is used to collect tunnel inventory items such as tunnel identification, age and level of service, classification, geometric data, inspection, load rating and postings, navigation, and structure type. SNTI inventory items require the following information: 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.

[12] FHWA, Rule: 80 FR 41349 “National Tunnel Inspection Standards,” 2015.

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

[14] FHWA-HIF-15-006, “Specifications for National Tunnel Inventory,” http://www.fhwa.dot.gov/bridge/inspection/tunnel/, 2015.

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 are maintained in the NTI database to track tunnel conditions throughout the U.S. General requirements of the program can be summarized as:

- 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 quality control and quality assurance programs.
- Establishing responsibilities for tunnel inspection organization and qualifications for tunnel inspection personnel.
- Training and national certification of tunnel inspectors.

Another reference for tunnel inspection and maintenance is the NCHRP Project 20-07/Task 261[15] report that 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 included for safety and emergency response system testing.

The NCHRP Project 20-07/Task 276[16] report was published in July 2010 and provides best practices for repairing and rehabilitating existing tunnel elements. The report focuses on structural and drainage repairs and provides detailed recommendations on the steps of the rehabilitation process.

In addition, the *American Railway Engineering Maintenance-of-Way Association (AREMA) Bridge Inspection Handbook*, Chapter 11–Tunnel Inspection[17] 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 need to be addressed related to external environment, internal tunnel safety, drainage, natural gas, portals, and main tunnel structure (tunnel shaft). The tunnel

[15] National Cooperative Highway Research Program (NCHRP), "Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspection," prepared for AASHTO Technical Committee for Tunnels (T-20), NCHRP Project 20-07, Task 261 Final Report, October 2009.

[16] NCHRP, "Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspection," prepared for AASHTO Technical Committee for Tunnels (T-20), NCHRP Project 20-07, Task 276 Final Report, July 2010.

[17] American Railway Engineering Maintenance-of-Way Association (AREMA), *AREMA Bridge Inspection Handbook*, Chapter 11–Tunnel Inspections, 2010.

inspection checklist includes soil/rock stability, clearances, drainage, tunnel floor, and conditions of structural components.

All available references provide common general inspection requirements, such as:

- Perform inspections regularly.
- Maintain records and inventories.
- Submit tunnel inventory and inspection data to FHWA.
- Report critical findings.
- Maintain current load ratings.
- Develop quality control and quality assurance programs.
- Establishing responsibilities for tunnel inspection.
- Training and certification of inspectors.

Inspection Types

Inspection type can be separated based on the priority—initial, routine, damage, in-depth, and special. The initial inspection is to establish the inspection file record and the baseline conditions for the tunnel. Follow-up routine inspections should provide comprehensive observations and measurements performed at regular intervals. Damage inspections identify hard-to-detect deficiencies using close-up inspection techniques. And special inspections are focused on defects and deficiencies related to safety or critical findings. Table 4-1 provides more details.

Table 4-1 *Inspection Types and Their Purpose*

Inspection Type	Purpose
Initial	Establish inspection file record and baseline conditions for tunnel.
Routine	Comprehensive observations and measurements performed at regular intervals.
Damage	Assess damage from events such as impact, fire, flood, seismic, and blasts. Assess structural damage resulting from environmental factors or human action.
In-Depth	Identify hard-to-detect deficiencies using close-up inspection techniques.
Special	Monitor defects and deficiencies related to safety or critical findings.
Fracture critical	Perform hands-on inspection of fractured critical member.
Underwater	Inspect underwater portion of bridge substructure.

Common types of general inspection practices include cleaning, field measurements, and establishing survey control.

- Cleaning – Debris, efflorescence, rust, or other foreign substances should be removed to observe the condition of the defect better. The appropriate tools and equipment should be used to remove corrosion and limit damage to any applied finishes. In many cases, wire brushes may be appropriate to remove corrosion; in other cases, foreign substances can be removed using water, solvent, compressed air, or another cleaning fluid in conjunction with a soft-bristled brush.

- Field measurements – After visually inspecting all exposed surfaces, the defects and deficiencies should be properly measured and recorded. The location of the defect is important for subsequent monitoring and repair work. For example, spalls in the concrete are characterized by their length, width, and depth. Length and width are noted for cracks. Corrosion of steel members is measured along the length and width. The depth of corrosion is measured. Similar measurements can be made on wood members to document any deterioration. Accurate measurements ensure quality results.
- Survey control – It is important to be able to locate a defect again after it has been documented. A survey control system helps locate defects during follow-up inspections, monitoring, or repairs. Most highway tunnels have a baseline or stationing system already established. Using this information, the tunnel inspectors can accurately record the location of the defects and deficiencies. To take this one step further, some tunnel facilities use wall panels with defined widths that can be used as part of the survey control system. By establishing a grid incorporating the panels, defects can be measured from the panel joints and their location converted to the stationing system.

The interval requirements for initial and routine inspections are contained in the NTIS. Table 4-2 summarizes these requirements.

Table 4-2 *Inspection Types and Their Frequency*[18]

Activity Type	Application	Interval
Initial Inspection	New tunnel	Prior to opening to traffic to the public
	Existing tunnel	Within 24 months of effective date
Routine Inspection	Default condition	Every 24 months over lifetime of tunnel
	Approved written justification	Possibly allow extension up to 48 months
In-depth Inspections	Complex tunnels and for certain structural and functional systems	Level and frequency to be established by Program Manager

[18] FHWA Rule: 80 FR 41349, National Tunnel Inspection Standards, 2015.

The tunnel inspection organization is responsible for establishing the inspection intervals for in-depth inspections based on the needs of the tunnel facility. Special and damage inspections are performed at the discretion of the tunnel owner. At a minimum, the initial inspection should consist of a sufficient number of observations and measurements to determine the physical and functional condition of the tunnel. These inspections are intended to be comprehensive, covering the structural, civil, mechanical, electrical and lighting, fire and life safety, security, signs, and protective systems.

Routine inspections shall be conducted at a regular 24-month period. For tunnels needing inspection more frequently than 24-month intervals, establish criteria to determine the level and frequency to 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.

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. 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 inspection may be necessary at some locations.

Inspection Techniques

Visual observations that include noting water leaks, sags, floor buckling, iron staining, and mineral deposits, and odors comprise the most common types of inspections. A more advanced technique is optical surveys. Tunnel optical surveys are laborious and time-consuming but can help document potential problem areas. These often follow visual observations and are used to confirm and document actual deformation numbers.

Tests can be specifically identified in the inspection procedures of important structural elements. These procedures establish baseline conditions and maintain a history of periodic measurements, which can be useful for gaging performance and indicating potential problems.

Inspection of Civil and Structural Elements

The SNTI defines condition states for tunnel liners, roof girders, columns and piles, cross passageways, interior walls, portals, ceiling slabs, ceiling girders, hangers and anchorages, ceiling panels, invert slabs, slabs on grade, invert girders, joints, and gaskets. Miscellaneous structural elements should be inspected periodically to maintain safety. These elements include structural connections, doors, windows, frames, staircases, roofs, floors, brackets and supports, machinery pedestals, structural finishes, ancillary buildings, and auxiliary tunnel structures. The tunnel inspection organization should develop written procedures for inspecting the elements defined by the SNTI and consult with the tunnel owner to develop procedures for inspecting any additional owner-defined elements.

This section covers various inspection procedures for multiple components/systems. Appendix A provides more details about inspection techniques. Additional information can also be found in Section 4 of the TOMIE Manual.[19]

Structural Materials

Structural elements consist of materials such as steel, concrete, timber, and masonry. Several material evaluation techniques are covered in the Manual for Bridge Evaluation (MBE). These techniques include various field tests, material sampling, and laboratory tests. The MBE discusses field tests for concrete, steel, and timber. Concrete field tests include strength methods, sonic methods, ultrasonic techniques, magnetic methods, electrical methods, nuclear methods, thermography, radar, radiography, and endoscopes. Steel field tests include radiography, magnetic particle examination, eddy current examination, dye penetrant examination, and ultrasonic examination. Timber field tests include penetration methods, electrical methods, and ultrasonic examination. It is recommended that these evaluation techniques be considered. Tests can be specifically identified in the inspection procedures of important structural elements to establish baseline conditions and maintain a history of periodic measurements, which might be useful for gaging performance and indicating potential problems.

In addition to visual inspection procedures, structural members should be periodically sounded with hammers to help identify hidden defects below the surface that may not be apparent from observations. After striking the surface with a hammer, structural elements will generally produce a fairly distinct sound. A clear ring generally indicates that competent material exists below the surface. Conversely, a dull thud or hollow sound typically indicates that the material below the surface contains a defect. A dull sound in concrete over an area might signify the presence of delamination where loose concrete could later spall. A hollow sound in timber might indicate a material with advanced decay. A dull thud from steel might indicate heavy corrosion, or in the case of a thin member, the sound might indicate that the steel member is not securely fastened or mounted. Once a dull sound is detected, the surface of the material should be further sounded to define the extent of the area impacted by the defect.

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

- Steel structures – Steel structures are affected by corrosion, cracks, buckles, and kinks. Other defects may also be present, such as leaks and protective system failures.
- Concrete structures – Common concrete defects include scaling, cracking, delamination, spalling, pop-outs, mud balls, efflorescence, staining, and honeycombing. Water leaks may be present with some of these defects, adversely impacting any reinforcing steel exposed to the leak. Additional information on concrete defects, including typical photographs, can be obtained from the American Concrete Institute (ACI).
- Timber structures – Timber defects include decay, insects, checks/splits, fire damage, hollow area, and leakage.
- Masonry structures – Masonry structure defects include masonry units, mortar, shape, alignment, and leakage.

Structural Elements

The structural elements contained in the NTI database include the following:

- Liners – The tunnel liner supports the ground around the tunnel and restricts groundwater infiltration into the tunnel. Many tunnels have a two-pass liner system consisting of an initial liner (or temporary support) and a final liner (or permanent support). Initial support is typically provided by shotcrete and rock bolts, ribs and lagging, and slurry walls. The final liner is usually made of either cast-in-place concrete liners or bolted and assembled precast concrete segments. The subsurface conditions can be obtained from published geologic reports, project geotechnical reports and test borings, and construction documents. The ground and groundwater conditions should be plotted along the tunnel profile with the locations of deficiencies noted. A geotechnical engineer should determine if the ground conditions are contributing to the problems and recommend solutions. The inspection techniques depend on the type of tunnel liner and are explained in detail in Appendix A.
- Roof girders – Inspect these elements using the methods previously described for structural concrete or steel materials.
- Columns and piles – Inspect these elements using the methods previously described for structural steel and concrete materials.
- Emergency corridors – The inspector should check for cracks, delamination, and spalls in the concrete walls, ceilings, and floors. Check for leaks. Look for a build-up of maintenance debris in the rooms. Examine the utilities, lights, electrical conduit, and safety systems for deterioration. Miscellaneous structural checks should be performed on all the structural connections, doors, windows, frames, roofs, floors, curbs and walkways, staircases, brackets and supports, and structural finishes.

- Interior walls – Concrete walls should be inspected using the methods previously described under structural concrete materials.
- Architectural finishes – Check the exposed substrate concrete for cracks, delamination, and spalls.
- Portals – A qualified geotechnical engineer or geologist should assist the inspection team when evaluating the potential for landslides. Inspect the walls, ceilings, and floors of the portal building for cracks, delamination, and spalls using the methods described for the appropriate structural material. Implement miscellaneous structural checks as appropriate.
- Tunnel ceiling structures – When inspecting ceiling structures, it is critical to carefully and thoroughly examine each component of the ceiling support system to ensure that the ceiling loads are being transferred into the support members as intended. Prior to conducting an inspection of ceiling elements, the inspector should review all pertinent drawings and procedures. Special attention should be given to hangers and anchorages, tunnel roof, ceiling girder, slabs, and panels.
- Tunnel invert structures – When inspecting invert structures, the size and location of the defects should be documented. Check the concrete for cracks, delamination, and spalls; use a hammer to sound random areas of the invert for delaminated concrete and sound areas around cracks and spalls.
- Joints and gaskets – Examine joints for deterioration, efflorescence, and moisture penetration. Check for joints at the transitions between segments and connections to ancillary buildings and at auxiliary structures. Check the concrete around the joint for cracks, spalls, and delamination.

Miscellaneous Structural Checks

Although these items are not specifically reported to FHWA for highway tunnel inspections, it is good practice to complete miscellaneous structural checks on structural connections, doors, windows, frames, roofs, floors, staircases, brackets and supports, and structural finishes in the tunnel, ancillary buildings, or auxiliary structures. These items should be included in the written inspection procedures developed by the tunnel owner:

Inspection of Mechanical Systems

The SNTI defines condition states for the ventilation systems and fans, drainage, and pumping systems, emergency generator systems, and flood gates. These items are contained in the NTI database. Miscellaneous mechanical elements should be inspected periodically to maintain safety. These elements include items such as plumbing, air conditioning, and heating. The tunnel inspection organization should develop written procedures for the elements listed in the SNTI and consult with the tunnel owner to develop procedures for inspecting owner-defined elements. It is important to review the operating and maintenance logs before inspecting mechanical systems. The inspectors should verify the performance of repairs or replacements noted in the logs.

Tunnel Ventilation

There are two basic types of mechanical ventilation systems—longitudinal and transverse, which can be combined or modified with semi-transverse systems. There also are single-point extraction systems that supplement the ventilation requirements for emergency conditions. Longitudinal systems use axial fans that discharge air parallel to the impeller rotation axis; transverse systems use centrifugal fans that discharge air at 90 degrees to the rotation.

Tunnel ventilation systems incorporate mechanical components such as fan motors, fan drive systems, fan shaft bearings, fan drive coupling, fan housings, local fan controls, dampers and damper drives, and sound attenuators. A ventilation system inspection should include, at a minimum, the following:

- Review the maintenance records for each piece of equipment and note any special or frequent previous maintenance problems.
- Note the physical condition of fans, airway, louvers, motor-operated dampers, and drive trains.
- Verify that each fan and the associated motor-operated dampers and components are operational.
- Perform vibration analysis on the fans, motors, and bearings during typical fan operations and inspect the fan drive system and bearings.
- Ensure that the airways, where accessible, are free of obstructions and debris.
- Test the operation of the carbon monoxide (CO) monitoring equipment.
- Check airflow (cfm) to ensure that ventilation design criteria are being met.

Tunnel Drainage

The tunnel drainage system is designed to remove water from the tunnel and consists of grates, scuppers, piping, drainage troughs, and pumps. Check if the drain lines are clear of debris and flush with water to ensure that water drains freely. Look for ponded water. Check the inlet grates for deterioration or broken ribs. Ensure the roadway drain piping is in good condition and free of debris. Document the location and extent of the defects.

- Pumps (general) – The major components of the tunnel pumps systems are the pumps, sump pits, pump piping, sump level indicators, and pump controls. Operate all pumps to verify that they are all functioning properly.
- Sump pumps – A sump pump is submersed in water and pumps water from a collection basin located in a low point where the water drains by gravity; sump pumps are used in the floor of the lower plenum to remove collected

water from the tunnel. When inspecting the sump pumps, the drainage drawings should be carefully reviewed to obtain a working understanding of how the drainage system works and where the sump pits are located.

Miscellaneous Mechanical Systems

It is good practice to perform miscellaneous mechanical system checks on all plumbing, air conditioning, and heating systems in the tunnel, ancillary buildings, or auxiliary structures. These items are commonly included in the owner-defined elements.

Emergency Generator Systems

A standby generator is a backup electrical generator system that operates when the power grid fails to deliver electricity. Emergency generators may operate on gasoline, diesel fuel, natural gas, or propane and supply enough electricity to operate the essential equipment and allow occupants to escape from the tunnel in an emergency, even when power from the grid fails. Emergency generators should have enough fuel to run for at least 24 hours.

An emergency generator system normally supports loads from fans, drainage pumps, fire pumps, alarms and communication systems, traffic control and surveillance, security and control systems, and emergency lighting. It is good practice to review the drawings and evaluate the standby capacity for the emergency generator. Overcapacity, on the order of 25%, is typical. When inspecting the emergency generator system, the inspector should:

- Evaluate the ability of the emergency power system to operate when the normal power fails by disabling the normal power supply (i.e., the power supply to any transfer switch or other means of transferring loads) and operating the emergency system with selected emergency loads for a sufficient period.
- Perform an internal inspection, check for hot spots, and note any deficiencies. Review the previous maintenance records to see if prior discrepancies have been corrected. Verify that all tests have been performed and meet industry standards, including NETA MTS-2011 and NFPA 110.
- Check that the lifting mechanism, gates, seals, seating, and all valves associated with the flood gates function as intended. Ideally, flood gates should be tested against a head of water equal to the maximum anticipated flood levels. Building a temporary water-tight bulkhead is a technique used for building up the water head against the gates for testing purposes.

Inspection of Electrical Systems

Inspection of electrical systems includes the electrical distribution system, the emergency distribution system, the tunnel lighting system and fixtures, and the emergency lighting system and fixtures. It is important to review the operating and maintenance logs prior to conducting inspections on electrical and lighting systems. Verify the performance of recent repairs or replacements noted in the logs.

The tunnel inspection organization should develop written procedures for the elements listed as part of the electrical system and for elements requested by the owner. Written inspection procedures should be developed with the assistance of a qualified electrician or specialty contractor due to the dangers posed by electric current and the inherent risks of electric shock.

Electrical Distribution Systems

Electrical systems are complex and contain multiple components that are potentially hazardous. The existing records and schematics should be carefully reviewed before conducting an inspection, and the inspectors must thoroughly understand of the system. Determine the need to conduct short-circuit, load-flow, reliability, and arc-flash studies as part of the inspection process. It is good practice to survey the electrical equipment and develop inspection methods that target the system's individual components.

The electrical system consists of the electrical equipment, wiring, conduit, and cable used for distributing electrical energy from the utility supply (service entrance) to the line terminals of the equipment. The system includes transformers, switchgear, switchboards, panel boards, motor control centers, starters, switches, and receptacles. General inspection recommendations include the following:

- Take voltage and load readings on the electrical system using any of the installed meters.
- Check that all indicator gauges on the transformers show that fluid levels, temperatures, and pressures are within operating range.
- Check for signs of damage and overheating of all equipment.
- Check utility structural support connections for corrosion or missing fasteners.
- Ensure that all enclosures and box covers are in place and secure and that conduits are not broken.
- Evaluate the condition of enclosures and conduit.
- For all large power systems, electrical safety operating diagrams should be posted to comply with OSHA and NFPA 70E.

- Check for conformity to NFPA 70, 70B, 70E, 72, 502, 520, and NETA MTS-2011.
- Check that adequate working space is provided in accordance with NFPA 70, Article 110, and that area around equipment is clear with no material stored in the working space. Visibly inspect wiring systems for damage and corrosion.
- Ensure that the electrical outlets are functional. Test all ground fault circuit interrupter (GFCI) type outlets to ensure they trip correctly.
- Examine the conduit support structure, including all clamps and supports. Ensure all conduit clamps are secure.
- Check all disconnect switches to ensure that the equipment is properly disconnected.
- Check that all sources of energy are isolated.
- Check all motor controllers for proper operation.
- Perform a thermographic (infrared) inspection for hot spots and an internal inspection and note any deficiencies. Verify that all tests meet industry standards, including NETA MTS-2011.

Emergency Power Distribution Systems

NFPA produces documents that are useful for maintaining, inspecting, and testing emergency power systems, including NFPA 110, Standard for Emergency and Standby Power Systems and NFPA 111, Standard on Stored Electrical Energy Emergency and Standby Power Systems. Review the electrical requirements for the tunnel, which vary by location. Generally, this is based on state or local building codes. It is good practice to reference, include, or summarize the requirements in the inspection documentation.

The emergency power distribution system consists of automatic transfer switches, panel boards, electrical equipment, and the associated wiring, conduit, and cable for providing electrical power in case of utility service failure. The major equipment included in this system consists of emergency generators and/or uninterruptible power supply systems. Emergency generators should be inspected as previously described under mechanical systems. The emergency power distribution system should refer to the techniques described for inspecting the electrical distribution system.

- Evaluate the ability of the emergency power system to operate when the normal power fails by disabling the normal power supply (i.e., the power supply to any transfer switch or other means of transferring loads) and operating the emergency system with selected emergency loads for a sufficient period.

- Perform an internal inspection and an inspection for hot spots and note any deficiencies. Have the same testing party review the previous maintenance records to see if prior discrepancies were corrected. Verify that all tests meet industry standards, including NETA MTS-2011 and NFPA 110.

Lighting Systems

Lighting systems are complex elements consisting of multiple components with potentially hazardous equipment. A failure of some components may limit the system's effectiveness as a whole. Review existing records and diagrams carefully prior to initiating the field work. It is important not to double count the emergency lighting fixtures or the normal lighting fixtures. When lighting fixtures are on for both normal and emergency use, it may be helpful to consider these as part of the emergency lighting system to avoid double counting the light fixtures. Written procedures should be developed to address this issue.

The major components of the tunnel lighting system include lamps, ballasts, lenses, housings, wiring, and controls. The lighting system conditions should be evaluated with a combination of visual observations, data provided by the tunnel operators via maintenance reports, and in-depth testing procedures, including the measurement of lighting levels at the roadway surface.

The most efficient way to test the lighting system is to operate the lighting and associated controls, simulating the sequential operation of the system over a 24-hour cycle from nighttime to daylight, and observe the changes in the illumination levels on the roadway surface as compared to the system design criteria.

Inspection of Fire Detection and Life Safety Systems

Fire and life safety and emergency systems are complex interconnected systems. The design and as-built records should be carefully reviewed along with the vendor-supplied information before conducting the inspection. For these systems, the general condition of the system components should be assessed along with the state of general housekeeping. Observe the general condition of the equipment and the enclosures, including cabinets and panels. Access panels, doors, seals, and latches should be checked for rusted, deteriorated, broken, or otherwise damaged components.

Fire Systems

Fire systems can be categorized into those that alert and detect in response to fire and those that provide protection from the harmful effects of fires. NFPA produced several documents that are useful for maintaining, inspecting, and testing fire systems—NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways; NFPA 70, National Electric Code; NFPA 72, National Fire Alarm and Signaling Code; NFPA 101, Life Safety Code; NFPA 110, Standard for Emergency and Standby Power Systems; and NFPA 111, Standard on Stored Electrical Energy Emergency and Standby Power Systems.

Review the fire and life safety requirements established by the agency having jurisdictional authority, which varies by location. Generally, this is a written agreement between the state DOT, the state fire marshal, and the local fire department. It is good practice to reference and summarize the requirements in the inspection documentation.

Maintenance logs that document system checks should be reviewed prior to conducting the inspection. Deficiencies in the logbook should be noted. When inspecting fire systems, it is good practice to be on the lookout for unprotected electric wires, improper storage of flammable materials, and products that produce toxic chemicals when burned (e.g., plastics such as PVC or HDPE materials).

- Fire detection – NFPA 72, National Fire Alarm Code provides information on inspecting and testing fire alarms and signaling devices.
- Fire protection – Proper inspection of these systems requires familiarity with NFPA 25, Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems and other applicable NFPA standards. Local codes may require inspection and commissioning by the fire department or other qualified fire system inspectors.

Inspection of Tunnel Security and Operation Systems

The systems included under security and operation involve surveillance, control, and communication equipment, such as closed-circuit television cameras (CCTV), telephones, radios, incident response and detection devices, air quality monitors, the control center and systems, and the Supervisory Control and Data Acquisition (SCADA) system.

Inspecting the tunnel security and operation systems should include visual observations and measurements specific to each component. The inspector should:

- Verify that the CCTV cameras, telephones, radios, or other communication devices are operational.
- Inspect traffic signals for proper operation during all phases.
- Verify that over-height detector systems are not triggering at any heights just below the desired setting and they are triggering at or just above the desired setting.
- Software changes for additional programming and periodic upgrades are required to maintain flexibility and reliability of system operation.

The requirements for tunnel security should be established by the tunnel owner. A tunnel-specific vulnerability assessment is a valuable tool for determining the security needs of the tunnel. Each tunnel facility typically develops its own set of security requirements based on security protocols and policies established by the tunnel owner.

Inspection Documentation

All general field inspection/repair notes, consisting of a chronology of events, must be kept in a bound field book or an electronic logbook. 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 shall be maintained in one location.

The three types of field notes required for effective tunnel inspections are:

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

23 Code of Regulations (CFR) Part 650, Subpart E – NTIS[20] is a minimum standard for the proper safety inspection and evaluation of all highway tunnels (in accordance with 23 United States Code (U.S.C.) 144(h)) and the requirements for preparing and maintaining an inventory (in accordance with 23 U.S.C. 144(b)).

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 repair recommendations.

Following are examples of elements in an inspection report:

- Critical finding – Defects that require "immediate" action, including possible closure of the tunnel where safety or structural concerns are identified using criteria established in the 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.

[20] FHWA Rule: 80 FR 41349, National Tunnel Inspection Standards, 2015.

- Priority repair – Conditions for which further investigations, 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 reduce future maintenance costs. Elements that do not comply with code requirements are also priorities for repair.
- Routine repair –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 – the report should contain descriptions of the various deficiencies found, their locations, and their severity. Any special testing, such as concrete strength, freeze-thaw analysis, or petrographic analysis, should be included with the findings for the record.
- Mechanical inspections – the general condition and operation of all equipment should be described, and deficiencies noted. Specialized testing required to effectively determine the operational condition of the equipment, such as vibration testing and oil analyses, should be included for the record.
- Electrical inspections – the general condition and operation of all 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 levels measured to recommended levels should be provided to the owner. Remediation work that may accompany testing and inspection should be included.

Recommendations for repair or rehabilitation of the tunnel components found to be deficient or not meeting 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.

Condition Rating

Critical findings and condition state ratings are used to represent the condition of tunnel components. A critical finding is a significant safety or structural concern that must be acted upon and reported in accordance with the NTIS.

Condition states are used to represent the condition of an element at the time it was inspected. Condition states as defined in the SNTI are good, fair, poor, and severe. The conditions descriptions are listed below:

- Good condition – no notable distress
- Fair condition– isolated breakdowns or deterioration
- Poor condition – widespread deterioration or breakdowns without reducing load capacity
- Severe condition – The condition warrants a structural review to determine the effect on the strength or serviceability of the element or tunnel, OR a structural review has been completed and the defects impact the strength and serviceability of the element or tunnel

Structural and civil elements in severe condition usually warrant a structural review to determine if there are any impacts to strength or serviceability. For functional systems in severe condition, evaluate the safety and serviceability of the element. Condition states are recorded in the inspection report and database and then submitted to FHWA. Critical findings require immediate attention per agency and NTIS requirements.

According to the National Bridge Inspection Standards (NBIS), condition ratings are used to describe an existing bridge or culvert compared with its condition if it were new. The ratings are based on the materials, the physical condition of the deck (riding surface), the superstructure (supports immediately beneath the driving surface), and the substructures (foundation and supporting posts and piers). General condition ratings range from 0 (failed condition) to 9 (excellent). A structurally-deficient bridge is one for which the deck (riding surface), the superstructure (supports immediately beneath the driving surface) or the substructure (foundation and supporting posts and piers) are rated in condition four or less. The particular conditions are:

9 – Excellent Condition

8 – Very Good Condition – no problems noted

7 – Good Condition – some minor problems

6 – Satisfactory Condition – structural elements show some minor deterioration

5 – Fair Condition – all primary structural elements are sound but may have minor section loss, cracking, spalling, decay, infestation, or scour

4 – Poor Condition – advanced section loss, deterioration, spalling, decay, infestation, or scour

3 – Serious Condition – loss of section, deterioration, spalling, decay, infestation, or scour have seriously affected primary structural components; local failures are possible

2 – Critical Condition – advanced deterioration of primary structural elements; fatigue cracks in steel or shear cracks in concrete, severe decay or infestation in timber, or scour may have removed substructure support; unless closely monitored, it may be necessary to close the structure until corrective action is taken

1 – Imminent Failure Condition – major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability; bridge is closed to traffic, but corrective action may put the structure back in light service

0 – Failed Condition – out of service; beyond corrective action

The condition of an element, member, or component is an evaluation of its current physical state compared to the as-built (new) condition. The following guidelines are used in establishing an element's condition rating:

- Good – element is limited to only minor problems
- Fair – structural capacity of element is not affected by minor deterioration, section loss, spalling, cracking, decay, infestation, or other deficiency
- Poor – structural capacity of element is affected or jeopardized by advanced deterioration, section loss, spalling, cracking, decay, infestation, or other deficiency

In 2018, FTA published the *Transit Asset Management (TAM) Guidebook* that details the methods for transit agencies in measuring and reporting facility condition assessments to the National Transit Database (NTD).[21] The Transit Economic Requirements Model (TERM) scale is a five-point scale. FTA TERM Condition Assessment scale is presented in Table 4-3.

Table 4-3 *FTA TERM Condition Assessment Scale*

Rating	Condition	Description
5	Excellent	No visible defects, new or near new condition, may still be under warranty if applicable
4	Good	Good condition, but no longer new, may be slightly defective or deteriorated, but is overall functional
3	Adequate	Moderately deteriorated or defective, but has not exceeded useful life
2	Marginal	Defective or deteriorated in need of replacement, has exceeded useful life
1	Poor	Critically damaged or in need of immediate repair, is well past useful life

An asset is deemed to be in good repair if it has a rating of 3, 4, or 5 on this scale. Likewise, a facility is deemed to not be in good repair if it has a rating of 1 or 2.

[21] FTA, *TAM Facility Performance Measure Reporting Guidebook: Condition Assessment Calculation*, March 2018.

Evaluation of Tunnels

The cost of maintaining and improving tunnel systems must be balanced against available funding. Resources are limited for repairs and upgrades; therefore, repairs need to be evaluated and prioritized to make informed investment decisions. Evaluations are normally performed after the inspection data is 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 is lacking. Risk assessment techniques should include strategies for deploying, operating, maintaining, upgrading, and cost-effectively disposing of tunnel system components.

Critical Findings

The owner is required to establish a procedure to ensure that critical findings are addressed in a timely manner and actions have been taken, are underway, or are planned to resolve the issue. The critical findings are to be reported to FHWA within 24 hours. FHWA should be updated regularly, or as formally established, about the status of each critical finding until the issue is resolved. FHWA is to be provided with an annual report of the current status of each critical finding identified within the past year and each unresolved finding from a previous year.

In consultation with the tunnel owner, the tunnel inspection organization should have established written procedures for dealing with critical findings prior to the inspection. The inspection team must have communication protocols in place to ensure that immediate action can be taken to respond to a critical finding. Critical findings normally require one or more of the following actions be taken promptly:

- Close the tunnel until the severe defect is removed or repaired if such defect may impact users or user safety.
- Restrict the area from public access until the defect can be removed or repaired.
- Repair the structural member or address the functional or safety issue.

Detailed descriptions and photographs should be provided about the safety or structural concern. Identify appropriate actions or follow-up inspections and maintain a record of the actions taken to resolve or monitor the critical finding. For example, with a large concrete spall on the verge of falling into the roadway, the inspection team or tunnel operations personnel can block off the traffic, and the maintenance personnel or a specialty contractor can take down and remove the spalled concrete.

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 involving 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 and referenced in the subsequent section.

Several guidelines and standards provide details about potential defects and their maintenance methods.

The *AREMA Manual for Railway Engineering*, Chapter 1, Part 8, specifies the following potential defects: concrete spalls, rock falls, drainage, icing, and timber sets. Further details about a tunnel inspection checklist can be found in *AREMA Bridge Inspection Handbook*, Chapter 11 – Tunnel Inspection.[22]

SRT TSI Section 4.5 covers maintenance rules for railway tunnels. This includes identification of elements that are subject to wear, failure, aging, or other forms of deterioration or degradation; specification of the limits of use of the elements subject to deterioration and description of measures to prevent this deterioration; identification of elements relevant to emergency situations; and periotic checks of emergency equipment to ensure proper functioning.

The *TOMIE Manual*[23] provides details about tunnel operation, maintenance, inspection, and evaluation.

An effective maintenance program helps reduce costs, decrease the number of tunnel closures, increase public safety, and ensure 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)

[22] AREMA, *AREMA Bridge Inspection Handbook,* Chapter 11 – Tunnel Inspection, 2010.
[23] FHWA-HIF-15-005, *op. cit.*

Tunnel operation can be divided into two parts: normal operation and emergency response. Examples for both aspects of operation include:

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

An effective tunnel maintenance program reduces costs, decreases closures, and increases safety. Ideally, the maintenance strategies of a tunnel facility should strike a balance between preventative 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.

Section 5

Adopting a Standard for Transit Tunnel Inspection

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 there are a few best practice reports that could be adopted (Table 5-1). The FHWA/FTA *Highway and Rail 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 *AREMA Bridge Inspection Handbook* (Chapter 11) provides a tunnel inspection checklist.

FHWA developed the SNTI[24] to help safeguard tunnels and ensure reliable service levels on all public roads. The SNTI contains instructions for submitting tunnel inventory and inspection data to FHWA, which is maintained in the NTI database to track tunnel conditions throughout the U.S. The FHWA SNTI standard is recommended for rail transit tunnels.

Table 5-1 *Documents for Maintenance and Inspection of Rail Transit Tunnels*

Main Topic	Documents	Applicability
Inspection	*AREMA Bridge Inspection Handbook*, (Chapter 11)	Codes/standards and guidelines fully applicable
Inspection	FHWA/FTA, *Highway and Rail 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 National Tunnel Inventory (SNTI)	Supplementary standards and guidelines

The SNTI and the *TOMIE Manual* are the most comprehensive documents for tunnel maintenance and inspection; however, they need to be adjusted for transit agencies. Both documents are at a level appropriate to inspect and code the conditions of tunnel elements and for adequate national oversight and decision-making.

[24] FHWA-HIF-15-006, "Specifications for National Tunnel Inventory," 2015, http://www.fhwa.dot.gov/bridge/inspection/tunnel/.

Inventory Items

The SNTI provides a list of items (Table 5-2) arranged by category to be useful for inspectors in the field. Identification items are used to identify and locate the tunnel. The SNTI provides 18 items, but not all are applicable for transit tunnels.

Table 5-2 *Tunnel Identification Items*

Identification Items	Applicable for Transit Tunnels?
I.1 Tunnel Number	Yes
I.2 Tunnel Name	Yes
I.3 State Code	Not necessary
I.4 County Code	Not necessary
I.5 Place Code	Not necessary
I.6 Highway Agency District	Rather information about transit agency
I.7 Route Number	Rather line code
I.8 Route Direction	Yes
I.9 Route Type	Not necessary
I.10 Facility Carried	Not necessary
I.11 LRS Route ID	No
I.12 LRS Mile Point	Yes, Mile Post (MP)
I.13 Tunnel Portal's Latitude	Yes
I.14 Tunnel Portal's Longitude	Yes
I.15 Border Tunnel State or Country Code	Not applicable
I.16 Border Tunnel Financial Responsibility	Not applicable
I.17 Border Tunnel Number	Not applicable
I.18 Border Tunnel Inspection Responsibility	Not applicable

Age and Service Items define when the tunnel was constructed and reconstructed and the tunnel level of service. The SNTI provides eight items, some of which are strictly related to highway operation and not applicable for transit tunnels (Table 5-3).

Table 5-3 *Tunnel Age and Service Items*

Age and Service Items	Applicable for Transit Tunnels?
A.1 Year Built	Yes
A.2 Year Rehabilitated	Yes
A.3 Total Number of Lanes	Not necessary
A.4 Annual Average Daily Traffic	Not applicable
A.5 Annual Average Daily Truck Traffic	Not applicable
A.6 Year of Annual Average Daily Traffic	Not applicable
A.7 Detour Length	Yes
A.8 Service in Tunnel	Transit only

Classification Items define the owner, operator, and highway classification of the tunnel. The SNTI provides eight items, but not all are applicable for transit tunnels (Table 5-4).

Table 5-4 *Tunnel Classification Items*

Classification Items	Applicable for Transit Tunnels?
C.1 Owner	Not applicable
C.2 Operator	Not applicable
C.3 Direction of Traffic	Not applicable
C.4 Toll	Not applicable
C.5 NHS Designation	Not applicable
C.6 STRAHNET Designation	Not applicable
C.7 Functional Classification	Not applicable
C.8 Urban Code	Not applicable

Geometric Data Items define the geometric data of the tunnel (Table 5-5).

Table 5-5 *Tunnel Geometric Data Items*

Geometric Data Items	Applicable for Transit Tunnels?
G.1 Tunnel Length	yes
G.2 Minimum Vertical Clearance over Tunnel Roadway	yes
G.3 Roadway Width, Curb-to-Curb	Rather track clearance
G.4 Left Sidewalk Width	Rather emergency walkways
G.5 Right Sidewalk Width	Rather emergency walkways

Inspection Items describe when inspections were performed and the type of inspection(s) performed (Table 5-6).

Table 5-6 *Tunnel Inspection Items*

Inspection Items	Applicable for Transit Tunnels?
D.1 Routine Inspection Target Date	Yes
D.2 Actual Routine Inspection Date	Yes
D.3 Routine Inspection Interval	Yes
D.4 In-Depth Inspection	Yes
D.5 Damage Inspection	Yes
D.6 Special Inspection	Yes

Load Rating and Posting Items are related to load rating and posting of the highway tunnel. The SNTI provides 12 items, but not all are applicable for transit tunnels (Table 5-7). Load noted in this section is referenced in AASHTO's *Manual for Bridge Evaluation.*

Table 5-7 *Tunnel Load Rating and Posting Items*

Load Rating and Posting Items	Applicable for Transit Tunnels?
L.1 Load Rating Method	Not applicable
L.2 Inventory Load Rating Factor	Not applicable
L.3 Operating Load Rating Factor	Not applicable
L.4 Tunnel Load Posting Status	Not applicable
L.5 Posting Load – Gross	Not applicable
L.6 Posting Load – Axle	Not applicable
L.7 Posting Load – Type 3	Not applicable
L.8 Posting Load – Type 3S2	Not applicable
L.9 Posting Load – Type 3-3	Not applicable
L.10 Height Restriction	Not applicable
L.11 Hazardous Material Restriction	Not applicable
L.12 Other Restrictions	Not applicable

Structure Type and Material Items are related to tunnel shape and the adjacent materials surrounding the tunnel. The SNTI provides five items; all are applicable for transit tunnels (Table 5-8).

Table 5-8 *Tunnel Structural Type and Materials Items*

Structure Type and Material Items	Applicable for Transit Tunnels?
S.1 Number of Bores	Yes
S.2 Tunnel Shape	Yes
S.3 Portal Shapes	Yes
S.4 Ground Conditions	Yes
S.5 Complex	Yes

Elements

The SNTI provides a list of tunnel elements arranged by general element type and material and in accordance with their physical location in the tunnel to facilitate ease of use by tunnel inspectors in the field.

Table 5-9, Condition State Definition, lists defects and condition state language specific to that element. Only those defects that are appropriate for a specific element are listed. Each defect is then associated with four condition states and descriptive language based on the material type to recognize that the defect is dependent on the material and its severity. For instance, cracking can occur in steel, concrete, and timber, but the type of cracking will differ, and the element condition state language reflects these differences. The severity of a defect can vary within an element and is described and quantified using four different condition states.

Table 5-9 *Tunnel Condition State Definition*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
General Condition	Good condition – no notable distress	Fair condition – isolated breakdowns or deterioration	Poor condition – widespread deterioration or breakdowns without reducing load capacity	Severe condition – warrants structural review to determine effect on strength or serviceability of element or tunnel, OR structural review completed and defects impact strength and serviceability of element or tunnel

Limits of condition states 1 through 3 are typically well-defined for each defect. Condition state 4 is reserved for instances when the defect's conditions are beyond the limits of those defined in Conditions states 1 through 3, and a structural review is recommended or has been performed and reduced strength or serviceability exists.

Structural Section

This section in the SNTI is broad and defines all tunnel structural elements and the methodology for determining total elements quantities and condition state quantities (Table 5-10). As those are structural elements, all can be applied to transit tunnels. For each tunnel, the inspector will identify which elements are applicable and evaluate that element accordingly.

Table 5-10 *Tunnel Structural Elements*

Element Type	Element #	Element Name	Unit of Measure
Liners	10000	Steel Tunnel Liner	area, ft^2
	10001	Cast-in-Place Concrete Tunnel Liner	area, ft^2
	10002	Precast Concrete Tunnel Liner	area, ft^2
	10003	Shotcrete Tunnel Liner	area, ft^2
	10004	Timber Tunnel Liner	area, ft^2
	10005	Masonry Tunnel Liner	area, ft^2
	10006	Unlined Rock Tunnel	area, ft^2
	10007	Rock Bolt/Dowel	Each
	10009	Other Tunnel Liner	area, ft^2
Tunnel Roof Girders	10010	Steel Tunnel Roof Girders	length, ft
	10011	Concrete Tunnel Roof Girders	length, ft
	10012	Prestressed Concrete Tunnel Roof Girders	length, ft
	10019	Other Tunnel Roof Girders	length, ft
Columns/ Piles	10020	Steel Columns/Piles	each
	10021	Concrete Columns/Piles	each
	10029	Other Columns/Piles	each
Cross Passageway	10030	Steel Cross Passageway	length, ft
	10031	Concrete Cross Passageway	length, ft
	10033	Shotcrete Cross Passageway	length, ft
	10034	Timber Cross Passageway	length, ft
	10035	Masonry Cross Passageway	length, ft
	10036	Unlined Rock Cross Passageway	length, ft
	10039	Other Cross Passageway	length, ft
Interior Walls	10041	Concrete Interior Walls	area, ft^2
	10049	Other Interior Walls	area, ft^2

Table 5-10 (cont.) *Tunnel Structural Elements*

Element Type	Element #	Element Name	Unit of Measure
Portal	10051	Concrete Portal	area, ft^2
	10055	Masonry Portal	area, ft^2
	10059	Other Portal	area, ft^2
Ceiling Slab	10061	Concrete Ceiling Slab	area, ft^2
	10069	Other Ceiling Slab	area, ft^2
Ceiling Girder	10070	Steel Ceiling Girder	length, ft
	10071	Concrete Ceiling Girder	length, ft
	10072	Prestressed Concrete Ceiling Girder	length, ft
	10079	Other Ceiling Girder	length, ft
Hangers and Anchorages	10080	Steel Hangers and Anchorages	each
	10089	Other Hangers and Anchorages	each
Ceiling Panels	10090	Steel Ceiling Panels	area, ft^2
	10091	Concrete Ceiling Panels	area, ft^2
	10099	Other Ceiling Panels	area, ft^2
Invert Slab	10101	Concrete Invert Slab	area, ft^2
	10109	Other Invert Slab	area, ft^2
Slab-on-Grade	10111	Concrete Slab-on-Grade	area, ft^2
	10119	Other Slab-on-Grade	area, ft^2
Invert Girder	10120	Steel Invert Girder	length, ft
	10121	Concrete Invert Girder	length, ft
	10122	Prestressed Concrete Invert Girder	length, ft
	10129	Other Invert Girder	length, ft
Joints	10130	Strip Seal Expansion Joint	length, ft
	10131	Pourable Joint Seal	length, ft
	10132	Compression Joint Seal	length, ft
	10133	Assembly Joint With Seal	length, ft
	10134	Open Expansion Joint	length, ft
	10135	Assembly Joint Without Seal	length, ft
	10139	Other Joint	length, ft
Gaskets	10140	Gaskets	length, ft

The SNTI describes Condition State definitions for each element. In this report, only a few examples are presented, but in the developed standards, all details should be included. Visual assessments may be supplemented with non-destructive or destructive testing results for all elements.

Steel tunnel liner Condition State Definitions are presented in Table 5-11. Cast-in-place or precast concrete or shotcrete tunnel liner condition state definitions are presented in Table 5-12, and timber, masonry, and unlined rock tunnel liner condition state definitions are in tables 5-13, 5-14, and 5-15, respectively.

Table 5-11 *Steel Tunnel Liner Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Corrosion	None	Freckled rust; corrosion of steel has initiated	Section loss evident, or pack rust present but does not warrant structural review	Warrants structural review to determine effect on strength or serviceability of element or tunnel, OR structural review completed and defects impact strength and serviceability of element or tunnel
Cracking	None	Crack has self-arrested or been arrested with effective arrest holes, doubling plates, or similar	Identified crack exists that is not arrested but does not warrant structural review	
Connection	Connection is in place and functioning as intended	Loose fasteners or pack rust without distortion present but connection in place and functioning as intended	Missing bolts, rivets, or fasteners, broken welds, or pack rust with distortion but does not warrant structural review	
Distortion	None	Distortion has received structural review and has been mitigated	Distortion has received structural review and does not require mitigation	
Leakage	Dry surface	Saturated surface indicating seepage may be present or evidence of past seepage	Fully saturated surface with seepage	Seepage could range from dripping to flowing

Table 5-12 *Concrete Tunnel Liner Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Delamination/ Spall/ Patched area	None	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter; patched area sound	Spall greater than 1 in. deep or greater than 6 in. diameter; patched area unsound or showing distress; does not warrant structural review	Warrants structural review to determine effect on strength or serviceability of element or tunnel, OR structural review completed and defects impact strength and serviceability of element or tunnel
Exposed Rebar	None	Present without measurable section loss	Present with measurable section loss but does not warrant structural review	
Efflorescence/ Rust Staining	None	Surface white without build-up or leaching without rust staining	Heavy build-up with rust staining	
Cracking (Liners)	Width less than 0.012 in. or spacing greater than 5.0 ft	Width 0.012–0.10 in. below spring line or spacing of 1.0–5.0 ft	Width greater than 0.10 in. below spring line or greater than 0.012 in. above spring line or spacing of less than 1 ft	
Distortion	None	Distortion has received structural review and has been mitigated	Distortion has received structural review and does not require mitigation	
Leakage	Dry surface	Saturated surface indicating seepage may be present or evidence of past seepage	Fully saturated surface with seepage	Seepage could range from dripping to flowing

Table 5-13 *Timber Tunnel Liner Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Decay or Rot	None	Decay started in timber sets or lagging; no fungus growth or discoloration present	Decay has resulted in loss of strength, deflection or crushing of element but not of a sufficient magnitude to affect strength and serviceability of tunnel; fungus growth and discoloration present	Warrants structural review to determine effect on strength or serviceability of element or tunnel, OR structural review has been completed and defects impact strength and serviceability of element or tunnel
Voids	None	Small voids may exist in annular space behind lagging	Large voids may exist in annular space behind lagging	
Cracks/ Splits/Checks	None	Cracks, splits, or checks exist in timber sets or lagging	Cracks, splits, or checks exist in timber sets or lagging and have impacted strength and/ or serviceability but do not warrant structural review	
Timber Distortion	No off-set or misalignment between timber members (good compression fit)	Off-set or misalignment between timber members may exist but is 0.125 in. or less	Off-set or misalignment between timber members may exist and is between 0.125 in and 0.25 in.	
Insect Infestation	None	Infestation has started in timber sets or lagging	Infestation exists in timber sets or lagging and has produced loss of strength or deflection of element but not of sufficient magnitude to affect strength and/or serviceability of tunnel	
Loose or Missing Connectors	None	Loose bolts or fasteners present, but connection is in place and functioning as intended	Missing bolts or fasteners but does not warrant structural review	
Leakage	Dry surface	Saturated surface indicating seepage may be present or evidence of past seepage	Fully saturated surface with seepage	Seepage could range from dripping to flowing

Table 5-14 *Masonry Tunnel Liner Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Efflorescence/ Rust Staining	None	Surface white without build-up or leaching without rust staining	Heavy build-up with rust staining	Warrants structural review to determine effect on strength or serviceability of element or tunnel, OR structural review has been completed and defects impact strength and serviceability of element or tunnel
Mortar Breakdown	None	Cracking or voids in less than 10% of joints	Cracking or voids in 10% or more of joints	
Split/Spall	None	Block or stone has split or spalled with no shifting	Block or stone has split or spalled with shifting but does not warrant structural review	
Patched Area	None	Sound patch	Unsound patch	
Masonry Displacement	None	Block or stone has shifted slightly out of alignment	Block or stone has shifted significantly out of alignment or missing but does not warrant structural review	
Distortion	None	Distortion has received structural review and has been mitigated	Distortion has received structural review and does not require mitigation	
Leakage	Dry surface	Saturated surface indicating seepage may be present or evidence of past seepage	Fully saturated surface with seepage	Seepage could range from dripping to flowing

Table 5-15 *Unlined Rock Tunnel Liner Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Rockfall	No unsound (drummy) rock; no blocks or slabs apparent; no shear zones in evidence; no displacements visible along joints, cracks	Any blocks or slabs tightly interlocked with surrounding rock and not in danger of separating from parent rock mass; any displacements along shear zones, joints, or cracks appear to be old (have come about prior to existence of tunnel); unsound rock (drummy) areas less than or equal to 10 ft in diameter	Any blocks or slabs not tightly interlocked with surrounding rock are small (less than 1 ft in diameter); displacements along shear zones, joints, or cracks have occurred since was constructed; unsound rock (drummy) areas greater than 10 ft in diameter	Warrants structural review to determine effect on strength or serviceability of element or tunnel, OR a structural review has been completed and defects impact strength and serviceability of element or tunnel
Patched Areas	None	Sound patches	Unsound patches	
Leakage	Dry surface	Saturated surface indicating seepage may be present or evidence of past seepage	Fully saturated surface with seepage	Seepage could range from dripping to flowing

Civil Section

This section defines tunnel civil elements and the methodology for determining total element and condition state quantities. The wearing surface, traffic barrier, and pedestrian railing are covered in the SNTI. It is believed that the items listed as civil elements are not applicable for rail transit tunnels. However, this section could be substituted with a track evaluation section along with emergency egress. Track inspection and evaluation should be performed according to FRA (49 CFR Part 213), Track Safety Standards or the AREMA standard;[25] emergency egress is covered in the accompanying report.[26]

In addition to structural elements listed by the SNTI, transit tunnel inspections should include bench walls and other structural elements not directly listed. The bench walls run portal-to-portal and are an essential component of

[25] Davis D., Wilk, S., et al., "Background Research and Analysis on Specifications and Guidelines for Track Inspection and Maintenance," P-18-012, Washington, DC, 2018.
[26] Wilk S., Jones, M.C., and Sammon, D., "Standards Development Program: Tunnel Egress," P-18-XXX, Washington, DC, 2018.

tunnels. The structures provide emergency egress from trains when necessary and access to trains and track for emergency and other personnel. The interiors of the bench walls house ducts that contain electrical wiring, equipment, cables, and other essential equipment. The bench walls are often made from concrete and should be inspected as a concrete component. If another material is used, the inspection should be adapted accordingly.

Mechanical System Section

This section defines tunnel mechanical system elements and the methodology for determining total element quantities and condition state quantities. The mechanical system elements, including ventilation system and fans, drainage and pumping systems, pumps, emergency generator system, and flood gate, are included by the SNTI.

The ventilation system may include the following subcomponents—fans, fan motors, fan controller, airways, sound attenuators, dampers, damper motor, damper controller, air quality monitoring equipment (CO), control panels, and conduit. The ventilation system condition state definition is presented in Table 5-16, and the fan condition state definition is presented in Table 5-17.

Table 5-16 *Ventilation System Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
System Condition	System is in good condition – no notable distress	System is in fair condition – isolated breakdowns or deterioration	System is in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting serviceability of element or tunnel	Warrants evaluation to determine effect on serviceability of element or tunnel or evaluation has determined there is an impact on serviceability of element or tunnel

Table 5-17 *Fans Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Fan Operation (includes fan belt, fan chain, fan bearing temperature, and/or fan drive temperature)	Operates on all speeds and in all modes with no noticeable temperature rise	Operates on all speeds and in all modes; requires manual restart or manual control to achieve this; drive(s) require some adjustment; more than normal play observed (If belt – minor wear/ deterioration to belt); less than 40-deg. F temperature rise form ambient temperatures during operation	Fan operates on at least one speed or operates only in manual mode; drive(s) require major adjustment; severe play and/ or belt/chain noise observed (If belt – moderate wear/ deterioration to belt); 40-80 deg. F temperature rise form ambient temperatures during operation	Fan will not operate on any speed; over 80-deg. F temperature rise for ambient temperatures during operation
Fan Condition	No notable distress	Isolated breakdowns or deterioration	System in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting serviceability of element or tunnel	Fan warrants evaluation to determine effect on serviceability of element or tunnel or evaluation has determined there is impact on serviceability of element or tunnel

Drainage and Pumping System includes storm drains, piping, pumps, and water treatment equipment for removing water that may enter the tunnel from the portals, vent shafts, and cracks in the tunnel lining. The condition state definitions of drainage and pumping system are presented in Table 5-18. In addition, the component that moves water entering the tunnel through portals, vent shafts, and cracks in the tunnel lining should be inspected. The condition state definitions of pumps are presented in Table 5-19.

Table 5-18 *Drainage and Pumping System Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
System Condition	System in good condition – no notable distress	System in fair condition – isolated breakdowns or deterioration	System in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting serviceability of the or tunnel	Warrants evaluation to determine effect on serviceability of element or tunnel or evaluation has determined there is an impact on serviceability of element or tunnel

Table 5-19 *Pumps Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Pump Operation (Includes sump pump, pump motor, pump controller, pump control panel, oil leakage, pump leakage, noise and vibration and temperature	Operates at all speeds and in all modes; shut-off valves operate freely and without binding; fair amount of noise and vibration velocity of 100 in./s or less; no oil leakage observed; no leakage observed at pump seal; no water leakage noted in immediate piping and valves; motor temperature within expected limits	Operates at all speeds and in all modes in a reduced capacity; shut-off valves operate with some resistance and binding but appear to fully open/seal; slightly rough noise and vibration velocity between 100 and 300 in./s; limited exterior staining from oil seepage at seals; limited exterior water seepage from seals with seals appearing wet; motor temperature slightly increased during motor operation	Operates intermittently or haltingly; shut-off valves difficult or impossible to operate; rough noise and vibration velocity in excess of 300 in./s; extensive exterior staining from oil seepage around seals; measurable water seepage around seals that can be quantified in drips per minute; motor temperature moderately above what is expected and/or hot spots of temperature exist	Pump will not operate; pooling of oil on exterior surfaces of seals or significant reduction of interior lubricant level; visible stream of water on exterior surfaces of seals or significant reduction of pump performance; motor temperature drastically increased, motor function is influenced

The emergency generator system may include the following subcomponents—fuel main storage tank, fuel day tanks, circulating fuel pumps, fuel tank venting, fuel tank sensors, coolant systems, exhaust manifold insulation and lagging, exhaust air louver and damper actuator, supply air louver and damper actuator, generator, generator control equipment, control panels, and conduit. Emergency generator and power system mechanical components consist of fuel delivery, fuel storage, an engine cooling system, and exhaust systems. The emergency generator provides a backup power source in the event of utility service failure to the tunnel. The mechanical systems support the proper operation of the generator to provide backup power. The emergency generator system condition state definitions are presented in Table 5-20.

Table 5-20 *Emergency Generator System Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
System Condition	System in good condition – no notable distress	System in fair condition – isolated breakdowns or deterioration	System in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting serviceability of element or tunnel	Warrants evaluation to determine effect on serviceability of element or tunnel or evaluation has determined impact on serviceability of element or tunnel

Flood gates are the actual gates, seals, mechanical components, and power supply of a flood gate system. The flood gates are typically located at each portal for each bore. The flood gates are usually used when the tunnel roadway is closed, and the bores are threatened with taking on water at the portals. The flood gate system condition state definitions are presented in Table 5-21.

Table 5-21 *Flood Gate Condition State Definitions*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
System Condition	System in good condition – no notable distress	System in fair condition – isolated breakdowns or deterioration	System in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting serviceability of element or tunnel	Warrants evaluation to determine effect on serviceability of element or tunnel or evaluation has determined impact on serviceability of element or tunnel

Electrical and Lighting Systems Section

This section defines tunnel electrical and lighting system elements and the methodology for determining total element quantities and condition state quantities. The electrical and lighting system elements, such as electrical distribution, emergency distribution, tunnel lighting, and emergency lighting, are included by the SNTI.

The electrical distribution system may include the following subcomponents—switchgear, unit substations, switchboard, motor control centers, starters, transformers, transfer switches, panelboards, conduits and raceways, and electrical outlets/receptacles.

The emergency distribution system may include the following subcomponents—Uninterruptable Power Supply (UPS), batteries, and battery charging equipment.

The condition state definitions for electrical and emergency distribution systems are presented in Table 5-22.

Table 5-22 *Condition State Definition for Electrical and Emergency Distribution Systems*

Defect	Condition State 1	Condition State 1	Condition State 1	Condition State 1
System Condition	The system is in good condition – no notable distress	The system is in fair condition – isolated breakdowns or deterioration	The system is in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting the serviceability of the element or tunnel	The condition warrants evaluation to determine the effect on serviceability of the element or tunnel or the evaluation has determined there is an impact on the serviceability of the element or tunnel

Lighting systems consist of the light fixtures, supports, bulb housings, lenses, light switches, junction boxes, wiring, conduit, cable, sensors, and controllers used to provide lighting for the tunnel. The tunnel lighting system may also include the following subcomponents: photo controls and remote ballasts. The condition state definitions for lighting systems are presented in Table 5-23.

Table 5-23 *Condition State Definition for Tunnel Lighting System*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
System Condition	System in good condition – no notable distress	System in fair condition – isolated breakdowns or deterioration	System in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting serviceability of element or tunnel	Warrants evaluation to determine effect on serviceability of element or tunnel or evaluation has determined impact on serviceability of element or tunnel

Lighting fixtures include the physical housing of the tunnel lights and their connections to the tunnel. Tunnel lighting fixture component supports include anchorage to the supporting member and connecting hardware for the component housing. The condition state definitions for tunnel lighting fixture are presented in Table 5-24.

Table 5-24 *Condition State Definition for Tunnel Lighting Fixture*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Component Supports	No deficient support conditions	Loose anchorage or component housing connection hardware	Missing anchorage or component housing connection hardware which does not result in unstable situation	Failed anchorage or component connection hardware which results in unstable situation
Corrosion	None	Freckled rust; corrosion of steel has initiated	Section loss evident, or pack rust present but does not warrant structural review	Warrants structural review to determine effect on strength or serviceability of element or tunnel, OR structural review has been completed and defects impact strength and serviceability of element or tunnel
Component Housing or Enclosure	No damages	Single crack	Multiple cracks	Holes present

The emergency lighting system may also include the following subcomponents—exit signs, batteries, support space sighting, and remote ballasts. For this element, a separate emergency lighting system is considered to be one system.

Emergency lighting fixture component supports include anchorage to the supporting member and connecting hardware for the component housing. When a lighting fixture serves the dual purpose of general and emergency tunnel lighting, it is only counted under the tunnel lighting fixture element. However, those fixtures will have an impact on both tunnel lighting system and emergency lighting system elements.

Fire/Life Safety/Security Systems Section

This section defines tunnel electrical and lighting system elements and the methodology for determining total element quantities and condition state quantities. The fire and security system elements, including fire detection, fire protection, emergency communications. operation, and security, are included by the SNTI.

Fire detection systems consist of control panels, initiating devices (heat and smoke detectors, pull-stations), notification appliances (strobes, horns), wiring, conduit, and cable used to detect a fire in the tunnel. The fire detection system may also include the following subcomponents: sensors, controls, and alarms. The condition state definitions for fire detection systems are presented in Table 5-25.

Table 5-25 *Condition State Definition for Fire Detection System*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Condition	System in good condition – no notable distress	System in fair condition – isolated breakdowns or deterioration	System in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting serviceability of element or tunnel	Warrants evaluation to determine effect on serviceability of element or tunnel or evaluation has determined impact on serviceability of element or tunnel
Detection Sensor Operations (heat and smoke detectors)	All detection sensors are operational		Detection sensors not operational in multiple zones	Detection Sensor Operations (heat and smoke detectors)

Fire protection systems consist of fire extinguishers, hose connections, storage tanks, fire hydrants, building sprinklers, pumping systems, piping, circulating pumps, and hose reels used as fire protection in the tunnel. The fire protection system may also include the following subcomponents: main fire pump, pressure maintenance/jockey pump, dry pipe valve, valves and tamper switches, storage tanks, tunnel standpipe, pressure relief and air release valves, backflow prevention, hose stations, hose reels, building sprinklers, fire department connections, and fire hydrants. The condition state definitions for fire protection systems are presented in Table 5-26.

Table 5-26 *Condition State Definition for Fire Protection Systems*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
System Condition	System in good condition – no notable distress	system in fair condition – isolated breakdowns or deterioration	System in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting serviceability of element or tunnel	Warrants evaluation to determine effect on serviceability of element or tunnel or evaluation has determined impact on serviceability of element or tunnel

The components of the emergency communication system include the communication device itself (i.e., intercom, radios, cell phone), receivers, wiring, and exchange devices. The emergency communications system may also include the following subcomponents: signs, controllers, speakers, and audio input equipment.

Tunnel operations and security systems consist of the equipment (CCTV cameras, telephones, radios) to communicate within and from the tunnel. The tunnel operations and security system may also include the following subcomponents—CCTV camera system, cell phone antennas, door access, controller, and radio.

Signs Section

This section defines tunnel sign elements and the methodology for determining total element quantities and condition state quantities. The elements of traffic guidance, egress signs, variable message boards, and lane signal are included by the SNTI. These elements will be different for transit tunnels and may need to be specified by transit agencies. A parallel report addressing tunnel emergency egress is going to be published in late 2018.[27]

Protective Systems Section

This section defines tunnel sign elements and the methodology for determining total element quantities and condition state quantities. The elements of steel corrosion protective coating, concrete corrosion protective coating, and fire protective coating are included by the SNTI.

The steel corrosion protective coating element is for steel elements that have a protective coating system, such as paint, galvanization, or other topcoat steel corrosion inhibitor. Effectiveness is an evaluation made by the inspector to classify the degree to which the protection system is functioning to protect the steel beneath. Protective coatings only apply to those elements listed under the structural and civil sections. The condition state definitions for steel corrosion protective coating are presented in Table 5-27.

Table 5-27 *Condition State Definition for Steel Corrosion Protective Coating*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Chalking	None	Surface dulling	Loss of pigment	Not applicable
Peeling/ Bubbling/ Cracking	None	Finish coats only	Finish and primer coats	Exposure of bare metal
Oxide Film Degradation Color/ Texture Adherence	Yellow-orange or light brown for early development; chocolate-brown to purple-brown for fully developed; tightly adhered, capable of withstanding hammering or vigorous wire brushing	Granular texture	Small flakes, ½ in. diameter	Dark black color Large flakes, ½ in. diameter or greater, or laminar sheets or nodules
Effectiveness	Fully effective	Substantially effective	Limited effectiveness	Failed, no protection of underlying metal

[27] Wilk, Jones, and Sammon, *op. cit.*

The concrete corrosion protective coating element is for concrete elements that have a protective coating applied. These coatings include silane/siloxane water proofers, crack sealers such as high molecular weight methacrylate (HMWM), or any topcoat barrier that protects concrete from deterioration and reinforcing steel from corrosion. Effectiveness is an evaluation made by the inspector to classify the degree to which the protection system is functioning. Protective coatings only apply to those elements listed under the structural and civil sections. The condition state definitions for concrete corrosion protective coating are presented in Table 5-28.

Table 5-28 *Condition State Definition for Concrete Corrosion Protective Coating*

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Wear	None	Underlying concrete not exposed, coating showing wear from UV exposure, friction course missing	Underlying concrete not exposed; thickness of coating reduced	Underlying concrete exposed; protective coating no longer effective
Effectiveness	Fully effective	Substantially effective	Limited effectiveness	Protective system has failed or no longer effective

The fire protective coating element is the coating applied on the tunnel elements to protect these elements from fire. Fire protection includes fireproofing spray. Protective coatings only apply to those elements listed under the structural and civil sections. The condition state definitions for fire protective coating are presented in Table 5-29.

Table 5-29 *Condition State Definition for Fire Protective Coating*

Defect	Condition State 1	Condition State 1	Condition State 1	Condition State 1
Effectiveness	Fully effective	Substantially effective	Limited effectiveness	Failed – no protection of underlying material

Section 6

Conclusions and Findings

Timely and reliable tunnel inspections are likely to uncover safety problems and prevent failures. The structural, geotechnical, and functional components and systems that make up tunnels deteriorate and corrode due to the harsh environment in which these structures exist. As a result, routine and thorough inspection of these elements is necessary to collect the data needed to maintain safe tunnel operation and to prevent structural, geotechnical, and functional failures.

As transit and highway tunnels continue to age, an accurate and thorough assessment of each tunnel's condition is critical to avoid a decline in service and maintain a safe, functional, and reliable transportation system. Ensuring timely and reliable tunnel inspections will result in substantial benefits by enhancing the safety of the traveling public and protecting investments in key infrastructure. Repairs or changes resulting from the inspections could lead to substantial economic savings.[28]

An industry working group of transit agencies that own tunnels and other tunnel experts was formed to discuss the findings and provide recommendations for this study. This working group shared their current practices for tunnel inspection and knowledge about tunnel systems. One of the working group members, the Massachusetts Bay Transportation Authority (MBTA), is working extensively on a manual for transit tunnel inspection using the SNTI and the *TOMIE Manual* as a basis and extending rating definitions from the SNTI to satisfy the FTA TERM five-point scale. MBTA also is developing procedures for tunnel maintenance, repair, and rehabilitation. Both the manual and the procedures are being developed in coordination with the Asset Management section of MBTA.

Based on the standards and guidelines comparison and working group discussion, the following conclusions are made:

- Finding 1: A standard or recommended practice that addresses recommendation R-16-01 should include reference to the SNTI and the *TOMIE Manual* as the most comprehensive documents for tunnel maintenance and inspection; however, they need to be adjusted for transit agencies. Both documents are at a level appropriate to inspect and code the conditions of tunnel elements and for adequate national oversight and decision-making. Both documents are dedicated for highway infrastructure and need to be adjusted accordingly when developing a standard to satisfy recommendation R-16-01. The modifications are tabulated under

[28] FHWA Rule: 80 FR 41349, "National Tunnel Inspection Standards," 2015.

"adopting a standard for transit tunnel inspection." In addition, there is a need for adding bench walls or other structural elements present in transit tunnels but not listed in FHWA documents.

- Finding 2: A comprehensive and consistent rating system for tunnel structural components is necessary. Therefore, FTA's TERM five-point scale for tunnel elements may be refined to incorporate rating conventions set by the SNTI. The SNTI condition is defined in a four-point scale—Good, Fair, Poor, and Severe; FTA's TERM is the five-point scale—Excellent, Good, Adequate, Marginal, and Poor. The advantage of the SNTI rating system is that all tunnel elements/components are well-defined using a four-point scale with defect definitions for each component.
- Finding 3: FTA may consider creating a standard or recommendation approved through the rule-making process that would become a part of the TAM requirement for rail tunnel inventory, similar to FHWA's NTI database of highway tunnels. Existing tunnel inventory is handled differently by each agency. A standard on inventory minimum requirements would be useful in evaluation and prioritization for rehabilitation. FTA may want to create a requirement for rail tunnel inventory such as FHWA's NTI database of highway tunnels or extend the NTD, which is currently focused on facilities, to include tunnels. Many elements in the NTI database could be used, but additions would need to be made for transit rail tunnels. APTA could conduct a follow-up survey with transit agencies to identify additional categories to include in the inventory.
- Finding 4: FTA may consider a third-party evaluator of potential new technologies. FTA could consider future research work comparing future groundwater intrusion mitigation technologies, tunnel inspection tools, and tunnel waterproofing techniques. The results can be distributed to all transit agencies with potential recommendations, including how a technology could be implemented to meet defined industry standards.

Appendix A

Inspection Techniques

Visual observations that include noting water leaks, sags, floor buckling, iron staining, mineral deposits, and odors comprise the most common types of inspections. A more advanced technique is optical surveys. Tunnel optical surveys are laborious and time consuming but can help document potential problem areas. Often, optical surveys follow visual observations and are used to confirm and document actual deformation numbers.

Inspection techniques depend on the type of components/systems to be inspected. Structural elements consist of materials such as steel, concrete, timber, and masonry. For example:

- Concrete field tests include strength methods, sonic methods, ultrasonic techniques, magnetic methods, electrical methods, nuclear methods, thermography, radar, radiography, and endoscopes. “Hammer knocking” is used to evaluate concrete strength by manually sounding with a hammer to detect hollow or weak concrete and voids.
- Steel field tests include radiography, magnetic particle examination, eddy current examination, dye penetrant examination, and ultrasonic examination.
- Timber field tests include penetration methods, electrical methods, and ultrasonic examination.

Tests can be specifically identified in the inspection procedures of important structural elements to establish baseline conditions and maintain a history of periodic measurements, which might be useful for gauging performance and indicating potential problems.

Inspection of Civil and Structural Elements

The SNTI defines condition states for tunnel liners, roof girders, columns and piles, cross passageways, interior walls, portals, ceiling slabs, ceiling girders, hangers and anchorages, ceiling panels, invert slabs, slabs on grade, invert girders, joints, and gaskets. Miscellaneous structural elements should be inspected periodically to maintain safety. These elements include structural connections, doors, windows, frames, staircases, roofs, floors, brackets and supports, machinery pedestals, structural finishes, ancillary buildings, and auxiliary tunnel structures. The tunnel inspection organization should develop written procedures for inspecting the elements defined by the SNTI and consult with the tunnel owner to develop procedures for inspecting any additional owner-defined elements.

Structural Materials

Structural elements consist of materials such as steel, concrete, timber, and masonry. Several material evaluation techniques are covered in the *Manual for Bridge Evaluation* (MBE). These techniques include various field tests, material sampling, and laboratory tests. The MBE discusses field tests for concrete, steel, and timber. Concrete field tests include strength methods, sonic methods, ultrasonic techniques, magnetic methods, electrical methods, nuclear methods, thermography, radar, radiography, and endoscopes. Steel field tests include radiography, magnetic particle examination, eddy current examination, dye penetrant examination, and ultrasonic examination. Timber field tests include penetration methods, electrical methods, and ultrasonic examination. It is recommended that these methods be considered. Tests can be specifically identified in the inspection procedures of important structural elements to establish baseline conditions and maintain a history of periodic measurements, which might be useful for gauging performance and indicating potential problems.

In addition to visual inspection procedures, structural members should be periodically sounded with hammers to help identify hidden defects below the surface that may not be apparent from observations. After striking the surface with a hammer, structural elements will generally produce a fairly distinct sound. A clear ring generally indicates that competent material exists below the surface. Conversely, a dull thud or hollow sound typically indicates that the material below the surface contains a defect. A dull sound in concrete over an area might signify the presence of delamination where loose concrete could later spall. A hollow sound in timber might indicate a material with advanced decay. A dull thud from steel might indicate heavy corrosion or, in the case of a thin member, that the steel member is not securely fastened or mounted. Once a dull sound is detected, the surface of the material should be further sounded to define the extent of the area impacted by the defect.

Steel Structures

Steel structures are affected by corrosion, cracks, buckles, and kinks. Other defects may also be present, such as leaks and protective system failures.

- Corrosion – Corroded steel varies in color from dark red to dark brown. Initially, corrosion is fine grained but becomes flaky or scaly as it progresses. Eventually, corrosion causes pitting in the member. The locations, characteristics, and extent of all corroded areas should be noted. The depth of severe pitting should be measured, and the size of any perforations caused by the corrosion recorded, as well as the remaining member section.
- Cracks – Cracks in the steel may vary from hairline thickness to a width sufficient to transmit light. In structural steel members, any type of crack

can be serious. It should be reported right away and evaluated by an engineer. Look for cracks radiating from holes, cuts, notches in support rods, and welds.

- Buckles and kinks – Buckles and kinks develop mostly due to damage from thermal strains, overload, or other load combinations that produce failure or yielding of the steel from collision damage, fire damage, or soil interaction.
- Leakage – Steel is impermeable; however, leaks can occur where water is able to penetrate through joints, cracks, or holes in the steel. The seals, gasket materials, and welds should be checked to determine if they are defective. Also, differential movements may be taking place that open the joint.
- Protection system – Steel is often protected by paint or galvanizing. Weathering steel can also be used. A failing paint system results in peeling, cracking, corrosion pimples, and excessive chalking. Galvanizing is typically applied in a kettle or vat containing molten zinc where the iron in the steel reacts with the molten zinc to form a tightly bonded alloy coating. Flaking and chipping are common galvanizing defects.

Concrete Structures

Common concrete defects include scaling, cracking, delamination, spalling, pop-outs, mud balls, efflorescence, staining, and honeycombing. Water leaks may be present with some of these defects, adversely impacting any reinforcing steel exposed to the leak. Additional information on concrete defects, including typical photographs, can be obtained from the American Concrete Institute (ACI).

- Scaling – Scaling is the local flaking or peeling of a finished surface of hardened concrete associated with the gradual and continual loss of mortar and aggregate. Scaling is considered light when the coarse aggregate below the surface is not exposed but severe when the coarse aggregate is exposed.
- Cracking – A crack is a linear fracture in the concrete created when the tensile forces exceed the tensile strength of the concrete. Cracks can occur during curing (non-structural shrinkage cracks), ground movement, or external loads (structural cracks). Cracks may extend partially or completely through the concrete member and may be active or dormant. If a crack is active, it will propagate in length, width, or depth over a measured period. If a crack is dormant, it will not change with time; however, some dormant cracks can further degrade if not repaired as moisture penetrates the crack causing additional damage from exposure to freeze/thaw cycles. A crack's direction relative to the axis of the structure should be observed and measured. The location, width, length, depth, and spacing between cracks should be measured and recorded. Based

on various observations and measurements, cracks can be classified. Common types of cracks found in tunnels include longitudinal, transverse, vertical, diagonal, and random. More details about tunnel cracks can be found in the *TOMIE Manual.*[29]

- Delamination – As fresh concrete hardens, water and air that are trapped below the surface can develop into subsurface voids. This often occurs when bleed water is trapped below the surface due to premature troweling, which reduces the permeability of the surface. These voids create weakened zones below the surface that can eventually detach and lead to concrete spalling. These areas of the concrete surface produce a hollow sound when struck by a hammer. Determine the extent of these areas and document them.
- Spalling – Spalling is the detachment of hardened concrete fragments that leave a shallow, roughly circular or oval-shaped depression in the concrete surface. Usually, the depression rim cuts roughly perpendicular to the surface; and the base is parallel or slightly inclined to the surface. Delaminated concrete is subject to spalling. Steel reinforcement may also be exposed where the spalling is severe. The inspector should record the location, width, length, and depth of the spalled area and note any exposed reinforcing.
- Joint spall – This is an elongated depression along an expansion, contraction, or construction joint. The defect should be inspected as described above for concrete spalling.
- Pop-outs – These are conical fragments that break out at the surface of the concrete and leave a small hole. A shattered aggregate particle will often be found at the bottom of this hole, adhering to the small end of the pop-out cone.
- Mud Balls – These are small holes created on the surface by the dissolution of clay balls or soft shale particles that were introduced into the concrete mix. Mud balls have similar effect on the surface of the concrete as a pop-out.
- Efflorescence – This is a deposit of water-soluble calcium hydroxide that forms on the concrete surface. It is usually white and emerges from the concrete as solution materials crystallize as salts. It may be caused by evaporation on one side of the concrete and a water supply on the other side. Efflorescence may also occur because of contaminates in the groundwater or de-icing salts. Salt crystal stalactites can form on tunnel ceilings from severe efflorescence.
- Staining – Staining is a discoloration of the concrete surface caused by dissolved materials passing through cracks and re-depositing the materials

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

on the surface as water emerges and then evaporates. Although staining can be of any color, brown staining usually signifies that corrosion is occurring in the underlying steel reinforcement.

- Honeycomb – Honeycombing occurs in concrete when the mortar does not completely fill the voids between coarse aggregate particles. As the shape of the aggregate is visible, it gives the concrete the honeycombed appearance.
- Leakage – Leakage occurs in regions of the concrete surface where water has penetrated through cracks, joints, or other imperfections in the concrete. It is important to note the temperature when checking for leaks. The full effect of leakage might not be known when temperatures are below freezing since ice can mask the effects of leaks. The portions of the concrete structure that are below the water table should be carefully checked at joints for leaks.

Timber Structures

Timber defects include decay, insects, checks/splits, fire damage, hollow area, and leakage.

- Decay – Decay is the primary cause of timber deterioration; it is produced by living fungi that feed on the cell walls of timber. Three categories of fungi are mold, stain, and decay fungi. Three types of wood rot caused by decay fungi are soft rot (least severe) and brown and white rot (most severe). With heavy decay, timber may become discolored and soft, and section loss may occur. The amount of decay and section loss should always be noted in the inspection report.
- Insects – The presence of insect infestation should be noted in the inspection records, and the type of insect should be recorded if known. An insect may be placed into a container or a picture taken for later identification. Saw dust or powdered dust on or around the timber members could indicate the presence of wood-eating insects, which should be noted. Photographs of the insect mounds may be used to document the extent of the damage. Termites and carpenter ants are common insects that can cause timber deterioration.
- Checks/splits – Checks are cracks in timber that extend partially through the timber member; the percentage of penetration through the member should be identified with checks. Cracks that extend completely through the member are called splits. Checks and splits result from shrinkage after drying or from the seasoning of timber and should be noted in the inspection report.
- Fire Damage – Fires can blacken and char timber and cause appreciable section loss. Fire damage is easily evaluated on most timber structures, but it can be time-consuming. The best way to ascertain the extent of

damage is to chip away at the charred remains in several locations and then measure the remaining undamaged timber section. The greatest section loss often occurs where two or more members have been fastened together.

- Hollow area – A hollow area usually indicates either advanced decay in the interior of timber or the presence of wood-eating insects. Hollow areas should be noted in the inspection report to show the size, location, and extent of damage in the hollow area.
- Leakage – Leaks occur in timber where water is penetrating through a joint, check, split, or some other defect, such as a knot.

Masonry Structures

Masonry structure defects include masonry units, mortar, shape, alignment, and leakage.

- Masonry Units – The individual stones, bricks, or blocks of masonry structures should be checked for displaced, cracked, broken, crushed, or missing units. Some types of masonry surfaces are susceptible to deterioration or weathering.
- Mortar – The mortar should be checked to ensure that it is effectively bonded to the masonry unit at the joint. It is particularly important to note cracked, deteriorated, or missing mortar.
- Shape – Masonry arches are primarily used in compression applications; flattened curvature, bulges in walls, or other shape deformations may indicate unstable conditions with tension cracks.
- Alignment – The vertical and horizontal alignment of the masonry should be checked visually. Plumb bobs and lasers may be useful tools for assessing these conditions.
- Leakage – Leaks often occur in regions of the masonry where water penetrates through joints, cracks, or other imperfections. Efflorescence accumulations might help locate areas with active leaks.

Tunnel Liner

The tunnel liner supports the ground around the tunnel and restricts groundwater infiltration into the tunnel. Many tunnels have a two-pass liner system consisting of an initial liner (or temporary support) and a final liner (or permanent support). Initial support is typically provided by shotcrete and rock bolts, ribs and lagging, and slurry walls. Usually, the final liner is made of either cast-in-place concrete liners or bolted and assembled precast concrete segments. The subsurface conditions can be obtained from published geologic reports, project geotechnical reports and test borings, and construction documents. The ground and groundwater conditions should be plotted along the tunnel profile with the locations of deficiencies noted. A geotechnical engineer should determine if the ground conditions are contributing to the problems and recommend solutions.

Steel Liners

Structural steel is not used as a final liner material due to its relatively high cost, fabrication requirements, and susceptibility to corrosion. Many rock tunnels in mountains have exposed steel liner plate above the spring-line to prevent rocks from falling onto the roadway. Older tunnels in soft ground, hard rock, or under water may have incorporated steel components as part of their initial support. Common temporary liner components include liner plates, steel ribs, columns, beams, and prefabricated shell elements. Many of these steel elements were not designed to be part of the permanent structural load-carrying component of the tunnel and were not sufficiently protected against corrosion. Typically, the temporary steel elements were covered or encased in concrete final liners. If structural steel components have been incorporated into the tunnel liner, these steel elements should be inspected using the previously described methods for structural steel materials.

Concrete Liners and Shotcrete

Precast concrete liners and cast-in-place concrete liners comprise the bulk of all permanent final lining systems installed in highway tunnels. Because of their availability, ease-of-use, durability, and relatively low cost, concrete liners have been installed in all types of tunnel projects. Shotcrete, also referred to as pneumatically sprayed concrete, is used for temporary support and as final liners in lightly loaded structures, such as a rock tunnel, that supports only the loose rock that could fall onto the roadway. Concrete liners should be inspected using the methods previously described for structural concrete materials.

Architectural Finish

Many concrete tunnel liners are covered by an architectural finish, such as ceramic tiles or metal panels. When inspecting these surfaces, it is recommended that the inspector use a hammer to sound the substrate concrete or a rubber mallet to tap on the tile finish. This should be done at multiple locations throughout the tunnel and near known defects or when defects are suspected. When hollow-sounding areas are detected, the limits of the areas should be defined. When documenting spalls, the size, maximum depth, and location of the spalls should be noted. If reinforcing steel is exposed, the amount of section remaining should be noted and the percentage of section loss provided. When inspecting cracks, the length, width, depth, and location should be documented. Cracks with moisture or corrosion staining should be noted. Visually inspect cracks for moisture, leakage, corrosion, staining, and efflorescence. Record the amount of active leakage in number of drips per minute or estimate the continuous rate of flow.

Segmental Rings

When inspecting precast tunnel segments, the concrete should be inspected using the techniques previously discussed. The joints of the precast concrete liners should be inspected for cracks and leaks. The joint hardware, such as end plates, bolts, and gaskets, of each segment should also be inspected. The connection bolts on fabricated concrete liners may be discolored due to moisture and humidity conditions in the tunnel. This condition does not downgrade the structural capacity of the bolt. Particular attention should always be given to bolts in regions of water leaks to check for loss of section. If losses in the section are observed, then this should be noted in the inspection report. The cross-sectional shape should be compared against the shape shown in the drawings to evaluate possible changes in cross-sectional shape.

Timber Liners

Timber liners have been installed in some mountain tunnels to prevent loose rock from falling onto the roadway. The timber liner may be composed of roof or ceiling sections with or without wall elements. Timber liners should be inspected using the methods previously described under structural timber materials.

Masonry Liners

Masonry tunnel liners have not seen much use for highway and transit tunnels since this method was largely supplanted by concrete technology that came into existence before many tunnels were built. Nevertheless, masonry structures are quite common at tunnel portals and other ancillary buildings. Masonry materials should be inspected using the methods previously described under structural masonry materials.

Unlined Tunnels in Hard Rock

Tunnels may be unlined in some hard rock applications; however, these tunnels typically need reinforcing to prevent loose rock from falling into the roadway. Rock bolts and dowels are used for this purpose. Support from timbers, steel plates, or shotcrete may also be used in limited areas of unlined tunnels to prevent rocks from falling onto the roadway. Unlined tunnels are self-supported by the competent rock. A qualified geologist or geotechnical engineer should assist the inspection team when inspecting self-supported rock tunnels. Identify the deficiencies in the rock mass that could potentially pose safety and stability problems or nuisance issues for maintenance of traffic. The cross-sectional shape of the tunnel should be monitored for potential changes by taking measurements at predetermined intervals (approximately 200-ft intervals).

The distances between the spring line and vertical sidewalls should also be measured at specific points; the locations should be permanently marked.

Other Structural Elements

Roof Girders

A roof girder is the main horizontal support for a flat tunnel roof. Roof girders support the tunnel roof and the loads from the backfill, surcharge, and traffic above. Girders are used to support a deck system, and these girders can be steel or concrete. Inspect these elements using the methods previously described for structural concrete or steel materials.

Columns and Piles

Columns and piles are vertical load-bearing elements that consist of concrete or steel components. Piles are embedded into the ground. Columns are free-standing members located above the ground level. Lateral bracing may be incorporated to stiffen the columns. Inspect these elements using the methods previously described for structural steel and concrete materials.

Emergency Corridors

Emergency corridors provide a means of escape from the tunnel. Parallel tunnels may be linked by cross passageways. In emergencies, evacuees can move to safety through a cross passage and escape through an adjacent tunnel. Therefore, these evacuation passageways should not be cluttered with objects or debris, and doors should be operable. These areas should be slightly pressurized to maintain positive air flow to prevent smoke from entering the escape route. This helps maintain a tenable environment for evacuees and emergency responders. The inspector should check for cracks, delamination, and spalls in the concrete walls, ceilings, and floors. Check for leaks. Look for a build-up of maintenance debris in the rooms. Examine the utilities, lights, electrical conduit, and safety systems for deterioration. If the passageway is pressurized, an operational check of this system is required. Miscellaneous structural checks should be performed on all the structural connections, doors, windows, frames, roofs, floors, curbs and walkways, staircases, brackets and supports, and structural finishes.

Interior Walls

The tunnel liner is in contact with the ground, whereas the interior walls are not. Interior walls are usually constructed using concrete materials. These walls separate opposing traffic, the travel way from the ventilation plenum, or the travel way from the emergency egress corridor. Written procedures should address the specific identification of interior walls and the survey control processes for reporting inspection findings. Concrete walls should be inspected using the methods previously described under structural concrete materials. Concrete walls should be inspected using a hammer to sound the substrate concrete or a rubber mallet to tap on the tile finish at random locations and areas adjacent to defects. When hollow-sounding areas are detected, the limits of these areas should be defined. Mark out these areas using marker or paint. Note the size, maximum depth, and location of the spalls and any exposed reinforcing steel. Check and document the percentage of section loss, if present, at exposed reinforcing steel. Document the length, width, depth, and location of cracks. Visually inspect for moisture, leakage, corrosion, staining, and efflorescence. Note any cracks with moisture penetration or corrosion staining. Record the amount of active leakage in number of drips per minute or measure the flow rate.

Architectural Finishes

Many concrete tunnel walls are not visible because they are covered by architectural finishes, such as ceramic tiles or metal panels. Tile walls should be checked for cracked, delaminated, or missing tiles that could indicate defects in the underlying substrate concrete. Missing tiles may result from moisture and water penetration through the concrete substrate. Check the exposed substrate concrete for cracks, delamination, and spalls. Look for spalled concrete behind missing tiles and at construction joints between wall segments where reinforcement steel may be exposed. The degree of surface deterioration and condition of anchor bolts should be checked on metal panels. Note all conditions described above in the inspection report.

Portals

Tunnel portals are located at the entrances and exits of the tunnel. When inspecting the portal facades, it is important to consider the condition of the elements above the roadway since spalls or falling objects from above could impact the safety of tunnel users. It also is important to document the condition of material outside and above the portals, especially if there are concerns about landslides. A landslide could easily damage the portal façade or portal buildings. A qualified geotechnical engineer or geologist should assist the inspection team when evaluating the potential for landslides. Inspect the walls, ceilings, and floors of the portal building for cracks, delamination, and spalls using the methods described for the appropriate structural material. Use a hammer to sound the walls at random locations and around defects. Look for debris build-up in the rooms. Examine the utilities, lights, and electrical conduit within the rooms for deterioration. Miscellaneous structural checks should be performed on all the structural connections, doors, windows, frames, roofs, floors, staircases, brackets and supports, and structural finishes within the portal buildings and auxiliary structures. Implement miscellaneous structural checks as appropriate.

Tunnel Ceiling Structures

Tunnel ceiling structures consist of slabs or panels supported by either girders or hangers and anchorages. Many tunnels were installed with ceilings above the roadway to create space for ventilation. This space, commonly referred to as the upper plenum, is used to exhaust air from or supply air to the tunnel. Sometimes the upper plenum also contains utilities. The inspector should ensure that all air distribution diffusers, registers, and passages are in good condition and free of debris accumulation. The structural elements of tunnel ceilings include either reinforced concrete ceiling slabs or precast concrete ceiling panels supported by either girders or hangers and anchorages. These structural support systems carry loads from their own weight, ventilation pressures, live loads from personnel, wind pressure from trucks, and earthquakes. Many ceiling structures are relatively heavy, providing stability when large trucks pass through the tunnel and create air pressure waves between the truck and the ceiling. Because the ceilings are located directly above the roadway, the potential exists for objects to fall onto the roadway. When inspecting ceiling structures, it is critical to carefully and thoroughly examine each component of the ceiling support system to ensure that the ceiling loads are being transferred into the support members as intended. It is advised that detailed written inspection and maintenance procedures be fully developed and completely implemented when tunnels have heavy ceilings elements installed over traffic. Prior to inspecting ceiling elements, the inspector should review all pertinent drawings and procedures.

Hangers and Anchorages

If the ceiling structure is supported with hangers and anchorages held by adhesive epoxy anchors, then these anchorages should be repaired in accordance with FHWA's Technical Advisory – Use and Inspection of Adhesive Anchors in Federal-Aid Projects. If anchors have pulled out or loosened, the tunnel owner should be immediately notified since this poses a significant safety concern. Remedial action may be necessary, such as installing new supports that incorporate mechanical anchorages with the hanger rods or a similar system that does not rely on epoxy in sustained tension. Exposed steel support system elements should be inspected for corrosion and section loss, as well as for missing bolts at the connection points for the support beams or the hangers and anchorages. Document the locations of missing bolts, deteriorated beams, or hangers. Verify that the hanger connections are intact and ensure that there is no vertical displacement in the embedded supports or exposed anchors. Visually inspect the hangers to determine if they are bowed. A bowed hanger possibly indicates the ceiling slab was pushed up from vehicle impact, air pressure, or other means. One method to verify hangers are in tension is by ringing each hanger. Ringing a hanger is done by lightly striking it with a mason's hammer. A hanger in tension will vibrate or ring like a bell when struck; while a hanger that is not loaded in tension because of a loose connection or other defect, will not ring. Rather, a dull thud will be heard. If the hanger does not ring, inspect the hanger carefully and verify that the ceiling system is structurally sound.

Tunnel Roof

If the tunnel has a ceiling support structure with hangers attached to the roof, check the connection locations of these supports at both ends (tunnel roof and ceiling slab or panel) for cracks, delamination, and spalls. Check the roof area in the vicinity of the hangers for cracks in the concrete, delaminated concrete, and spalls to verify solid embedment. Use a hammer to sound random areas and areas suspected of concrete defects adjacent to the hangers.

Ceiling Girder

A ceiling girder is the main horizontal support for the ceiling panels or slabs. These structural elements are used in place of hangers and anchorages. Ceiling girders use various structural shapes. They are usually steel or concrete and should be inspected using the methods previously described for structural concrete and steel materials.

Ceiling Slabs and Panels

Slabs are cast-in-place concrete elements, whereas panels are precast concrete elements. Both serve the same function in the ceiling system. The topside and underside of the ceiling should be inspected. Note the location of cracked or deteriorated ceiling panels. Document the length, width, and locations of cracks in the ceiling slab. Visually inspect for spalling. Note the size, maximum depth, location, and any exposed reinforcing steel details at the locations of the spalls. Note the locations of cracks; look for moisture penetration and corrosion staining. At random locations and adjacent to all defects, a hammer should be used to sound the substrate concrete or a rubber mallet to tap the tile finish. The top side of the ceiling panels and the ceiling support system are often examined from within the upper plenum. Check the top side of the ceiling panels for cracks, corrosion stains, efflorescence, spalls, disintegrated concrete, and evidence of moisture. Observe for displaced seals between the panels. Examine the ceiling support system for corrosion and section loss, as well as missing bolts. At the bottom face of the ceiling panels, inspect concrete surfaces using the methods previously described for structural concrete. Focus on the inspection techniques for scaling, cracks, delamination, and spalling. Check for exposed reinforcing steel at spalls and document the section loss. Visually inspect for moisture and corrosion staining at cracks and note efflorescence at crack locations.

Tunnel Invert Structures

Tunnel invert structures consist of slabs supported by girders or on grade. When the roadway is a structurally supported slab, the space below the supported roadway is used for ventilation and drainage. The supported invert slab acts like a bridge deck that carries traffic loads. When inspecting invert structures, the size and location of the defects should be documented. Check the concrete for cracks, delamination, and spalls; use a hammer to sound random areas of the invert for delaminated concrete and sound areas around cracks and spalls. Record the sizes and maximum depth of the spalls. Note any section loss for exposed reinforcing steel. If severe spalling is present, a sketch should be prepared to show the extent and location of the spalling. Note exposed reinforcing steel in the spalls and record any section loss. Cores may be needed to determine the chloride ion content before making recommendations for repair or replacement. Document the length, width, and location of all cracks and delamination. Check for signs of moisture penetration. Note all corrosion staining, dampness, map cracking, and efflorescence. Document the severity and locations of all other defects. Provide percentages of total invert area for map cracking, moisture penetration, efflorescence, and delamination. Check for excess debris accumulation resulting in standing water and confirm that the lower plenum is draining into the sumps.

Invert Slab

Inspect the topside and underside of the slab. The topside of the slab might be obscured by the wearing surface; nondestructive testing can supplement the inspection process. The tight space below the slab could also preclude direct inspection from below the slab in the lower plenum. Robotic video inspection techniques can be used to inspect tight spaces such as these. Examine the concrete slabs for cracks, delamination, and spalls. Use a hammer to sound random areas of concrete for delamination and sound the concrete adjacent to cracks and spalls. Note exposed reinforcing steel in the spalls and record any section loss. Check for signs of moisture penetration through the concrete. Also note corrosion staining, dampness, and efflorescence. Document the amount of active leakage in number of drips per minute or measure the flow rate. Check for areas of potential localized failure due to punching shear at large spall locations and where large potholes occur.

Invert Girder

An invert girder refers to the main horizontal support for the slabs. These steel or concrete girders should be inspected using the methods previously described for structural concrete and steel materials.

Joints and Gaskets

Joints are integral to many structural elements and used to simplify construction or accommodate strains from thermal movements. Joints are typically sealed or have gaskets to keep out water.

Joints

Examine joints for deterioration, efflorescence, and moisture penetration. Check for joints at the transitions between segments and connections to ancillary buildings, and at auxiliary structures. Check the concrete around the joint for cracks, spalls, and delamination. Use a hammer to sound the concrete adjacent to the joint. Check the position and condition of the joint material. Check the condition of sealants between precast panel members. Closely examine the alignment and check for signs of differential settlement, which can lead to other serious defects. Document the locations and severity of moisture penetration or joint deterioration.

Gaskets

There are many gasket types, such as lead, mastic, or rubber. Gasket materials can become dislodged from the joint due to water infiltrating through the joint and loosening of fastening bolts. Gaskets also can fail due to chemical or biological deterioration of the material. Structural movements of the liner can tear or otherwise distort the gasket and cause it to leak. Differential settlement often leads to other defects. Extra time should be spent investigating transition areas; for example, where the tunnel support conditions change at connections to buildings. The location of these areas should be evident from existing as-built drawings. Note all gasket deficiencies, including the length, width, and locations of cracks, loose or broken fasteners, and leaks of any kind.

Miscellaneous Structural Cracks

Although these items are not specifically reported to FHWA, it is good practice to complete miscellaneous structural checks on structural connections, doors, windows, frames, roofs, floors, staircases, brackets and supports, and structural finishes in the tunnel, ancillary buildings, or auxiliary structures. These items should be included in the written inspection procedures developed by the tunnel owner.

Structural Connections

Connection bolts, rivets, and welds should be carefully checked. Bolts on precast concrete, steel, and cast-iron liners may be discolored due to moisture and humidity conditions in the tunnel; however, the discoloration usually does not reduce the structural capacity of the bolt. Particular attention should be given to bolts in regions where leakage occurs as section loss might result. A bolt can be rung with a hammer to determine if it's tight, but it's preferable to use a wrench. Section loss and missing or loose bolts should be noted in the inspection report. Observe the condition of welds for cracks and tears. Dye penetrant inspection may help detect cracks. Coatings may protect welds from corrosion.

Doors

During an inspection, all doors and windows should be opened and closed to verify their operability. Some door components may be deteriorated, stuck, or inoperable. The door hardware should be checked to ensure that the latches sufficiently engage the door frame, and the door can be closed securely. The door and the frame might have corrosion, delamination, or section loss. Security sensors also should be checked to be sure they are operational.

Windows and Frames

Steel window frames may be corroded, deteriorated, or experience section loss. Some of these may be stuck or inoperable. When inspecting concrete window frames, check for cracks, delamination, and spalls in the concrete material. The condition of protective coatings should also be documented.

Stairs

Stairs are typically built with either reinforced concrete or steel. Reinforced concrete stairs sometimes have steel tread plates incorporated into the concrete. Inspect the rails, posts, and railing anchorages for missing or broken sections, damage and deterioration, cracks or corrosion, and section loss. Inspect for cracked welds at the connections and loose or missing bolts. Document the severity and location of defects.

- Concrete staircases – Inspectors should check concrete stairs for cracks, delamination, and spalls. Note exposed reinforcing steel in the spalls and record any observed section loss in the reinforcing steel. Check for signs of moisture penetration, corrosion staining, dampness, and efflorescence. Use a hammer to sound random areas of the stairs and check for delaminated concrete. Also, sound areas adjacent to defects such as cracks and spalls. Document the length, width, and location of all cracks and delamination. Record the area, maximum depth and location of all spalls along with the condition of exposed reinforcing steel. Document the severity and locations of all other defects, including moisture penetration, efflorescence, and corrosion staining. Examine the steel tread plates, if present, for adjacent spalls and looseness. Use a rubber mallet to tap the tread plates and note any separated or missing plates.
- Steel staircases – Inspectors should check steel stairs and ladders for corrosion and section loss of the steps and supports. Examine for crevice

corrosion between plates of the stairs. Document the severity and location of corrosion and section loss. Note the length, location, and spread distance of all crevice corrosion.

Roof

Check the roof of ancillary buildings or auxiliary structures for deterioration that would allow water to penetrate the roof into the building. Check that the water drainage system is functioning properly and not clogged with debris. Check the drains in the roof and the overflow scuppers in the barriers for debris accumulation. Inspect the barriers around the perimeter of the roof for deterioration. If present, examine expansion joints in the roof for debris accumulation and deterioration of the joint material. Look at the exterior surface of the exhaust stacks for defects or deteriorated materials. Note the location and severity of defects on the roof. Document locations of water penetration. Record the condition of the roof coating material and the drainage system.

Floors

Check concrete floors for cracks, delamination, and spalls. Note exposed reinforcing steel in the spalled areas and record any section loss. Check for signs of moisture penetration, corrosion staining, dampness, map cracking, and efflorescence. Use a hammer to sound random areas of the floor and check for delaminated concrete. Also, sound areas adjacent to defects to define the extent of the defect area. Examine the floors for evidence of distortion and settlement. Document the length, width, depth, and location of all cracks and delamination. Record the area, maximum depth, and location of all spalls along with the condition of exposed reinforcing steel. Document the severity and locations of all other defects, including moisture penetration, efflorescence, corrosion staining, and settlement.

Brackets and Supports

Brackets and supports are structural elements that are mounted against the ceiling or walls. They are used to support longitudinal ventilation fans, CCTV cameras, ITS signs, traffic signs, over-height detection signs, lighting supports, conduit supports, and fan or motor supports. Check for corrosion, dissimilar metals, cracks, buckles, and kinks. Dissimilar metals may promote corrosion at accelerated rates when not sufficiently insulated from stray electrical currents. Particular attention should be given to bolts in regions where leakage occurs to evaluate any section loss. A bolt can be rung with a hammer, but it’s preferable to use a wrench for checking the tightness. Observe the condition of welds for cracks and tears. Dye penetrant inspection may help detect cracks.

Machinery Pedestals

Check concrete pedestals for cracks, delamination, and spalls. Use a hammer to sound random areas of pedestals to check for delaminated concrete, Also, sound areas adjacent to defects. Examine the floors for signs of settlement. Note exposed reinforcing steel in the spalls and record any section loss. Check for signs of moisture penetration, corrosion staining, dampness, map cracking, and efflorescence. Document the length, width, and location of all cracks and delamination. Record the area, maximum depth, and location of all spalls along with the condition of exposed reinforcing steel. Document the severity and locations of all other defects, including moisture penetration, efflorescence, and corrosion staining.

Structural Finishes

Tiles should be checked to determine whether they pose a hazard to passing motorists since loose tiles can fall into the roadway. A good technique for inspecting tiles is to tap firmly on a select number of tiles in multiple locations using a rubber mallet. A scraper may facilitate the checking or removal of loose tiles.

Inspection of Mechanical Systems

The SNTI defines condition states for ventilation systems and fans, drainage and pumping systems, emergency generator systems, and flood gates. These items are contained in the NTI database. Miscellaneous mechanical elements should be inspected periodically to maintain safety. These elements include plumbing, air conditioning, and heating. The tunnel inspection organization should develop written procedures for the elements listed in the SNTI and consult with the tunnel owner to develop procedures for inspecting owner-defined elements. It is important to review the operating and maintenance logs before inspecting mechanical systems. The inspectors should verify the performance of repairs or replacements noted in the logs.

Each piece of equipment or machinery should be carefully inspected and operated; however, this activity should first be coordinated with tunnel facility personnel. The established lockout/tag-out procedures should be implemented to ensure safety and prevent damage and injury. Any equipment that cannot be operated should be identified, its physical condition noted, and such information reported as soon as practical following established communication protocols. Boiler units and pressure vessels can be dangerous; it is recommended that qualified specialists or specialty contractors be used as appropriate.

Tunnel Ventilation

There are two basic types of mechanical ventilation systems: longitudinal and transverse, which can be combined or modified with semi-transverse systems. Single-point extraction systems that supplement the ventilation requirements for emergency conditions are also available. Longitudinal systems use axial fans that discharge air parallel to the impeller rotation axis; and transverse systems use centrifugal fans that discharge air at 90 degrees to the rotation.

Tunnel ventilation systems incorporate mechanical components such as fan motors, louvers, motor-operated dampers, and drive trains. The fans can be centrifugal or axial. The inspection of the ventilation system should include, as a minimum, the following items:

- Review the maintenance records for each piece of equipment and note any special or frequent previous maintenance problems.
- Note the physical condition of fans, airways, louvers, motor-operated dampers, and drive trains.
- Verify that each fan and the associated motor-operated dampers and components are operational.
- Perform vibration analysis on the fans, motors, and bearings during typical fan operations and inspect the fan drive system and bearings.
- Ensure that airways, where accessible, are free of obstructions and debris.
- Test the operation of the carbon monoxide (CO) monitoring equipment.
- Check airflow (cfm) to ensure that ventilation design criteria are being met.

Fan Motors

The motor exterior and supports should be checked for paint failure and surface corrosion. Use a wrench to verify the tightness of the mounting bolts. Examine the motor, shaft, and shaft bearings for leaks. Check the motor housings, supports, and surrounding components for grease accumulation. Check the seals to see if they have failed or are displaced outward. If grease is present, investigate the cause. Check all flexible conduits for deterioration. Operate the motor to verify that it is functional. While testing, visually check the motor, shaft, and shaft bearings; record any abnormal movement. Listen for unusual noises such as humming or screeching from the motor or bearings. Listen to and feel the motor housing for abnormal vibrations or temperature.

Tunnel fans should be operated at all speeds and observed at safe distances. Avoid standing near drives. Follow appropriate safety precautions. Note whether a fan requires manual restart or manual control to operate. Watch out for metal-on-metal contact, such as when a fan wheel might contact the scroll or inlet cone and cause sparking.

Use a handheld infrared thermometer to check the motor's operating temperature. Many motors will be warm when operating properly, but excessive heat might indicate a defect. Inspect the cooling passages and screens for excessive dust and dirt build-up that could impede cooling.

- Oil and lubrication leakage – Observe signs of oil/grease leakage on the fan, drive housings, or fan support pads. Leakage could indicate over-filling, defective seals, or out-of-roundness. If the motor is heating up, the leaks might be contributing to the problem. Ensure that leaking oil or lubricant doesn't present a fire hazard.
- Noise and vibration – Any excessive noise or vibration should be noted. If possible, identify the source of the noise or vibration during fan start-up. Periodic or continuous vibration monitoring should be performed on rotating elements (e.g., fan, motor bearings, and drive components). Review the fan vibration analysis data from the maintenance logs. Note the severity of the defects found. If possible, diagnose the cause of any abnormal movement, noise, or vibration.
- Paint and corrosion – Observe the general condition of the fan, drives, supports, and guards. Note the percentage of clean and painted surface compared to rusted and deteriorated surface. Record any section loss.

Fan Drive Systems

There are two common types of fan drive systems—direct drive and indirect drive. Direct drive fans turn at the same speed as the motor and are common with axial fans. Indirect drive fans have gears driven by belts or chains and sprockets and are common with centrifugal fans.

For a fan belt drive, check the pulleys and housings for paint failure and surface corrosion. Examine the belts for cracks, uneven wear, separation, abrasion, or any other deterioration. Some belts have wear indicators. While operating the motor, visually and audibly check the belt for slippage. Listen for squealing noises while switching speeds. A burning smell or squealing could indicate improper belt tensioning (loose). Make sure the pulleys are aligned and not in contact with the housings.

For the fan chain and sprocket drive, check the housings for paint failure and surface corrosion. Examine the housings for oil leaks at splits or covers. Check the condition of the oil and the oil level in the housing. If possible, open the housing to check the chains and sprockets for wear. Some chains and sprockets have wear indicators. While operating the motor, listen for chatter noises coming from the chains, which may indicate the chain is loose.

Fan Shaft Bearings

Bearings are critical components for fan operation. Bearing life is expressed as the number of hours of operation before the first evidence of metal fatigue develops in the rings or rolling elements. Bearings should be of air handling quality, heavy-duty, and ball or roller type. Check the condition of any oil or grease and verify that correct levels are maintained. Examine bearing seals for oil leaks and adjacent components for grease accumulation. If lubrication is present, investigate the cause. Lubrication oil samples taken during oil changes assist in identifying:

- Viscosity breakdown caused by excessive time between oil changes and excessive heat build-up in bearings or drive
- Dirt contamination caused by an improperly sealed bearing or drive or lubricating oil not properly stored or handled prior to use
- Metal-to-metal wear indicated by a high ferrous particle count or high iron count
- Water contamination

Check for paint failure and surface corrosion on the bearings housing and supports. Use a wrench to verify the tightness of the mounting bolts and cap bolts. Look for signs of uneven tracking or belt and pulley wear. Use a handheld infrared thermometer to check for elevated bearing, belt, and drive temperatures. Check extended grease lines for condition and breakage.

During operation, listen for abnormal sounds, and watch for any abnormal movement or vibrations which indicate possible defects. If possible, diagnose the cause of any irregular noise, movement, or vibration.

Fan Drive Coupling

Check the couplings for paint failure and surface corrosion. Examine for lubrication leaks. Use a wrench to check the tightness of the bolts. During operation, observe the coupling for excessive movement through the full range of speeds. In shim-style couplings, inspect for broken shims, delamination, or other defects.

Fan Housings

The inspector should check all components of the fan housings for failed paint, corrosion, and section loss. Visually and audibly verify that there is no contact between the fan and housing or that there is no out-of-balance or otherwise abnormal movement of the fan during operation. Contact between the fan and the housing is most noticeable at higher speeds. Listen for debris inside the fan housing or evidence of water that may indicate blocked drain piping. Inspect housing for signs of excessive corrosion or fatigue cracking. Look for excessive dust or dirt build-up, which might indicate a lack of maintenance and exercising of the fans. Confirm that all safety guards and access doors and covers are in place. Never reach into or enter fan housings or approach unprotected belts or chain drives without first implementing lock-out tag-out procedures. Inspect the conduit in the fan housing room for corrosion, missing covers, and exposed wires.

Local Fan Controls

Check local fan controls for proper operation. Examine the enclosure for loose or deteriorating wiring. Ensure that the emergency stop control is functioning properly for each fan. Look for testing tags that may indicate defective equipment.

Dampers and Damper Drives

Verify that damper drives are operational. Check door chains for signs of distress. Ensure that louvers and damper doors close completely. Check for paint failure and surface corrosion on all components. Use a wrench to verify the tightness of bolts. Examine the motors, shafts, bearings, and reducers for lubrication leaks. Check the seals to see if they have failed or if they are displacing outward. If grease is present, investigate the cause of the leak. Check oil levels. Make sure the reducer breather is functioning properly. Ensure that the rubber seals on the damper louvers are intact. Check the alignment of the damper blade indicator.

Sound Attenuators

Noise from fans is transmitted through the ventilation system. The portion of noise reaching the roadway is usually attenuated to a large degree by the ductwork and the ambient noise level within the tunnel. Sound attenuators are used to protect the surrounding neighborhoods from noise. Sound readings should be taken at a time when the noise level is of most concern, such as during the night when the noise levels in the neighborhood are at their lowest. Noise levels should be taken with the largest number of fans operating under non-emergency conditions.

Tunnel Drainage

The tunnel drainage system is designed to remove water from the roadway and consists of grates, scuppers, piping, drainage troughs, and pumps. Check if the drain lines are clear of debris and flush with water to ensure that water drains freely. Look for ponded water. Check the inlet grates for deterioration or broken ribs. Ensure the roadway drain piping is in good condition and free of debris. Document the location and extent of the defects.

Pumps (General)

The major components of tunnel pumps systems are the pumps, sump pits, pump piping, sump level indicators, and pump controls. Operate all pumps to verify they are functioning properly.

During testing, visually and audibly check for abnormal sounds or movement in the pumps and motors. Check that pumps operate at all speeds and in all modes. Shut-off valves should operate freely without binding or unusual noise. Extreme noise and vibration might be a sign of pending bearing or motor failure.

Manually run the pump from the local control panel as well as any remote panel. If possible, manually raise the sump float to activate the pump with the control in the ‘auto’ position. Note any excessive noise or vibration during pump operation. Confirm indicator lights on the control panels (local and remote) are properly lit. Ensure all local disconnects are not corroded and are functioning properly. If possible, check the tank floats for proper operation. Examine all conduits in the pump room for corrosion or other defects.

Examine the pump motors, shafts, and bearings for lubrication leaks. Check if seals are bulging or have failed. If grease is present, investigate the cause of the leak. Check the pump and pipe components for leaks or evidence of leaks. Examine the pump, pump components, pump supports, pipes, and pipe supports for corrosion and section loss. Use a wrench to verify the tightness of bolts. Review the most recent pump vibration analysis data. Periodic or continuous vibration monitoring should be considered for pumps rated over five horsepower.

Observe the general condition of the pump, motor, supports, and guards. Note the percentage of clean and painted surfaces compared to rusted and deteriorated surfaces. Check the condition and functionality of all valves and gauges. Confirm all valves associated with the pump have been recently lubricated and operate freely. Check the piping for security and installation of vibration control and expansion devices. For base-mounted pumps, note any significant leakage around the pump seal. Observe any leakage in piping, valves, and pipe accessories.

Assess the general housekeeping of the mechanical space and particularly the area around the pump. Be particularly observant of safety (fall) hazards and obstacles to pump access and maintenance. Also, assess the amount of debris in the sump. Document the severity of all defects.

Sump Pumps

A sump pump is submerged in water and pumps water from a collection basin located in a low point where the water drains by gravity; sump pumps are used in the floor of the lower plenum to remove collected water from the tunnel. For a multiple bore tunnel, the same low-point sump may be shared between the bores; or each bore could have its own drainage and pumping systems. The sump pump might connect to a holding tank, or it might be directly connected to the sewer system. A one-way check valve prevents the drainage water from flowing back into the system once the pumps are turned off. When inspecting the sump pumps, the drainage drawings should be carefully reviewed to understand how the drainage system works and where the sump pits are located.

All pump components, related supports, and system piping should be checked for damage, corrosion, and deterioration. Inspect all components for excess calcium deposits. Inspect the fasteners associated with the pumps and piping for corrosion and security. Confirm the sumps are free of debris and sludge that could hinder the performance or prevent the collection of water. Operate the sump pump to verify that it is functional, free from excess noise and vibration, and that water is being removed from the sump. Examine the check valve and piping for leaks. Check that the pumps operate on all speed settings and in all modes. Shut-off valves should operate freely and without binding. Extreme noise and vibration might be a sign of pending bearing or motor failure. Document the severity of all defects.

Emergency Generator Systems

A standby generator is a backup electrical generator system that operates when the power grid fails to deliver electricity. Emergency generators may operate on gasoline, diesel fuel, natural gas, or propane.

Emergency generators supply enough electricity to operate essential equipment and allow occupants to escape from the tunnel in an emergency, even when power from the grid fails. Emergency generators should have enough fuel to run for at least 24 hours.

The emergency generator system normally supports loads from fans, drainage pumps, fire pumps, alarms and communication systems, traffic control and surveillance systems, security and control systems, and emergency lighting. It is good practice to review the drawings and evaluate the standby capacity of the emergency generator. Overcapacity, on the order of 25%, is typical. When inspecting the emergency generator system, the inspector should:

- Evaluate the ability of the emergency power system to operate when the normal power fails by disabling the normal power supply (i.e., the power supply to any transfer switch or other means of transferring loads) and operating the emergency system with selected emergency loads for a sufficient period.

- Perform an internal inspection, check for hot spots, and note deficiencies. Review the previous maintenance records to see if prior discrepancies have been corrected. Verify that all tests have been performed and meet industry standards, including NETA MTS-2011 and NFPA 110.

Flood Gates

In some tunnels, flood gates are installed at the portals to limit rising waters from flooding the tunnel. Flood gates typically contain a gatehouse, lifting mechanism, flood gate, seating mechanism in the roadway, dewatering valve, and drainage shut-off valve. The gates themselves are steel and designed to withstand the hydraulic forces during a flood event.

Check that the lifting mechanism, gates, seals, seating, and all valves associated with the flood gates function as intended. Ideally, flood gates should be tested against a head of water equal to the maximum anticipated flood levels. Building a temporary watertight bulkhead is a technique used for building up the water head against the gates for testing purposes.

Miscellaneous Mechanical Systems

It is good practice to perform miscellaneous mechanical system checks on all plumbing, air conditioning, and heating systems in the tunnel, ancillary buildings, or auxiliary structures. These items are commonly included in the owner-defined elements.

Plumbing

The inspection of the plumbing system should be conducted according to applicable plumbing code requirements, and the following should be checked:

- Review the maintenance records for the plumbing system and note any special or frequent maintenance problems.
- Note the physical condition of the bathroom fixtures, water heaters, and drainage system.
- Verify that the plumbing fixtures are operational.
- Check the pipes for leaks, corrosion, damaged fittings, and loose brackets.
- Ensure that valves, gauges, and gaskets are functioning properly.
- Look for watermarks on tunnel surfaces to identify locations of plumbing system leaks.

Heating, Ventilating, and Air Conditioning (HVAC) Units

HVAC elements in support spaces include fans and dampers, filters and coils, and controls. The HVAC equipment should be operated at all speeds and all modes. Confirm that change-over from heating to cooling modes occurs as the thermostat is cycled. Confirm fan operation and note any vibration or unusual noise. Observe damper operation, noting binding of dampers or loose or poorly adjusted linkage. Assess damper leakage and confirm gravity back-draft dampers return to the closed position when fans are turned off.

- Filter and coils – Visually assess the cleanliness of the air filters and coils on air handling equipment. Confirm all filters are in place and assess the air leakage around poorly fitting filter racks. For coils equipped with drain pans, observe the cleanliness of the pan, and confirm the drain is flowing freely.
- Control – Note the temperature/comfort level of the space served by the unit. Confirm the unit is maintaining the temperature set point. Cycle thermostat and observe the ability of equipment to respond to changing set points. If dampers are interlocked with ventilation fans, observe the response of the interlocked equipment with the primary equipment operation.
- Overall condition – Observe the general condition of the equipment, including interior surfaces of air handling equipment and access doors, latches, and sealing gaskets. Note that all access panels are secure, doors seal tightly, and latches work freely. Note the percentage of clean and galvanized/anodized/painted surfaces compared to rusted and deteriorated surfaces. Assess the general cleanliness of the space where the equipment is located.

Air Conditioning

The inspection of the air conditioning systems in control rooms and other locations should include the following items:

- Review the maintenance records for each piece of equipment and note any special or frequent previous maintenance problems.
- Note the physical condition of air handling units, condensing units, packaged units, chillers, pumps, cooling towers, exposed air distribution systems, cooling piping, and terminal units.
- Verify that the system is operational. Note that the temperature during the inspection may limit operation or proper verification.
- Perform vibration analysis and inspections on chillers, cooling towers, and pumps.
- During scheduled oil changes – perform lubrication oil analysis on all (major) bearing lubricants.

Heating

The inspection of the support area heating system should include the following items:

- Review the maintenance records for each piece of equipment and note any special or frequent maintenance problems.
- Note the physical condition of air handling units, pumps, steam and water distribution systems, terminal units, boilers, exposed air distribution systems, heating piping, and steam converters.
- Boilers can be dangerous; therefore, a qualified boiler inspector certified by the National Board of Boiler and Pressure Vessel Inspectors should inspect each boiler, boiler room, and pressure vessel. Check the operational efficiency of all boilers and related systems to ensure that these units are operating in the appropriate range. The boiler inspector should verify that all systems related to the boiler (e.g., breeching, make-up, de-aeration, steam traps) are functional and operating properly and efficiently.
- Verify that the system is operational. Note that the temperature during the inspection may limit operation or proper verification.

Inspection of Electrical Systems

Inspection of electrical systems includes the electrical distribution system, the emergency distribution system, the tunnel lighting system and fixtures, and the emergency lighting system and fixtures. It is important to review the operating and maintenance logs prior to conducting inspections on electrical and lighting systems. Verify the performance of recent repairs or replacements noted in the logs.

The tunnel inspection organization should develop written procedures for the elements listed as part of the electrical system and for elements requested by the owner. Written inspection procedures should be developed with the assistance of a qualified electrician or specialty contractor due to the dangers posed by electric current and the inherent risk of electric shock.

Electrical Distribution Systems

Electrical systems are complex and contain multiple components that are potentially hazardous. The existing records and schematics should be carefully reviewed before conducting an inspection, and the inspectors must thoroughly understand the system. Determine the need to conduct short-circuit, load-flow, reliability, and arc-flash studies as part of the inspection process. It is good practice to survey the electrical equipment and develop inspection methods that target the system’s individual components.

The electrical system consists of the electrical equipment, wiring, conduit, and cable used for distributing electrical energy from the utility supply (service entrance) to the line terminals of equipment. The system includes transformers, switchgear, switchboards, panel boards, motor control centers, starters, switches, and receptacles. General inspection recommendations include the following:

- Take voltage and load readings on the electrical system using any of the installed meters.
- Check that all indicator gauges on the transformers show that fluid levels, temperatures, and pressures are within operating range.
- Check for signs of damage and overheating of all equipment.
- Check utility structural support connections for corrosion or missing fasteners.
- Ensure that all enclosures and box covers are in place and secure and that conduits are not broken.
- Evaluate the condition of enclosures and conduit.
- For all large power systems, electrical safety operating diagrams should be posted to comply with OSHA and NFPA 70E.
- Check for conformity to NFPA 70, 70B, 70E, 72, 502, 520, and NETA MTS-2011.
- Check that adequate working space is provided in accordance with NFPA 70, Article 110, and the area around equipment is clear with no material stored in the working space. Visibly inspect wiring systems for damage and corrosion.
- Ensure that the electrical outlets are functional. Test all ground fault circuit interrupter (GFCI) type outlets to ensure they trip correctly.
- Examine the conduit support structure, including all clamps and supports. Ensure all conduit clamps are secure.
- Check all disconnect switches to ensure that the equipment is properly disconnected.
- Check that all sources of energy are isolated.
- Check all motor controllers for proper operation.
- Perform a thermographic (infrared) inspection for hot spots and an internal inspection and note any deficiencies. Verify that all tests meet industry standards, including NETA MTS-2011.

Electrical Equipment

Each piece of electrical equipment should be carefully inspected and operated; however, this activity should first be coordinated with tunnel facility personnel. The established lockout/tag-out procedures should be implemented to ensure safety and prevent damage and injury. The electrical equipment should be test operated (e.g., tunnel fans, pumps, lighting). Also, check that the generator operates within acceptable limits for output voltage. Equipment that cannot be operated should be identified, and its physical condition noted.

The major components of the tunnel electrical system include switchgear, switchboards, transformers, generators, uninterruptible power supplies, panel boards, disconnect switches, and motor control equipment. The electrical equipment should be assessed based upon a combination of visual observations, measurements, and tests. Equipment operation, maintenance reports and daily logs, and any in-depth testing procedures (e.g., thermographic inspection, contact resistance testing, and generator load testing) should be assessed, as well.

Observe the general condition of the electrical equipment, including interior surfaces of equipment and access doors, latches, and sealing gaskets. Check that all access panels are secure, doors seal tightly, and latches work freely. Observe the general condition of the electrical equipment enclosures. Note the percentage of clean and galvanized/anodized/painted surfaces compared to rusted and deteriorated surfaces. Assess the general housekeeping of the electrical rooms and support spaces, paying particular attention to the immediate area around the equipment.

Miscellaneous Electrical System Checks

Although these items may not be specifically reported to FHWA, it is good practice to perform electrical system checks on all miscellaneous electrical components and appliances in the tunnel, equipment rooms, maintenance corridors, plenums, ancillary buildings, and auxiliary structures. Check the condition of electric receptacles, wires, switches, circuit breakers, and meters for evidence of overloading, overheating, damage, deterioration, and corrosion. Look for evidence of arcing, discoloration, or other signs that might indicate the electrical components are defective. These items are commonly included in the owner-defined elements.

Emergency Power Distribution Systems

NFPA produces documents that are useful for maintaining, inspecting, and testing emergency power systems, including NFPA 110, Standard for Emergency and Standby Power Systems and NFPA 111, Standard on Stored Electrical Energy Emergency and Standby Power Systems. Review the electrical requirements for the tunnel, which vary by location. Generally, this is based on State or local building codes. It is good practice to reference, include, or summarize the requirements in the inspection documentation.

The emergency power distribution system consists of automatic transfer switches, panel boards, electrical equipment, and the associated wiring, conduit, and cable for providing electrical power in case of utility service failure. The major equipment included in this system consists of emergency generators and/or uninterruptible power supply systems. Emergency generators should be inspected as previously described under mechanical systems. The emergency power distribution system should also refer to the techniques described for inspecting the electrical distribution system.

- Evaluate the ability of the emergency power system to operate when the normal power fails by disabling the normal power supply (i.e., the power supply to any transfer switch or other means of transferring loads) and operating the emergency system with selected emergency loads for a sufficient period.
- Perform an internal inspection and look for hot spots; note any deficiencies. Have the same testing party review the previous maintenance records to see if prior discrepancies were corrected. Verify that all tests meet industry standards, including NETA MTS-2011 and NFPA 110.

Lighting Systems

Lighting systems are complex elements consisting of multiple components with potentially hazardous equipment. A failure of some components may limit the effectiveness of the system as a whole. Review existing records and diagrams carefully before initiating the fieldwork. It is important not to double count the emergency lighting fixtures or the normal lighting fixtures. When lighting fixtures are on for both normal and emergency use, it may be beneficial to consider these as part of the emergency lighting system to avoid double counting the light fixtures. Written procedures should be developed to address this issue.

The major components of the tunnel lighting system include lamps, ballasts, lenses, housings, wiring, and controls. The lighting system conditions should be evaluated through a combination of visual observations, data provided by the tunnel operators via maintenance reports, and in-depth testing procedures, including measuring lighting levels at the roadway surface.

The most efficient way to test the lighting system is to operate the lighting and associated controls by simulating the sequential operation of the system over a 24-hour cycle from nighttime to daylight and observing the changes in the illumination levels on the roadway surface compared to the system design criteria. Following are some processes to consider for lighting system testing:

- Measure the light levels within tunnels using an Illuminating Engineering Society (IES) LM-50 device and compare the results against the requirements of IES RP-22.

- Measure the light levels at intervals suggested by IES LM-50.
- Measure the light levels at emergency egress exits and compare them with the IES Handbook recommendations.
- Inspect for visible damage, including corroded or damaged housings, loose attachments, broken lenses, and burnt-out bulbs. Examine for exposed wiring where the conduit has pulled out of the fixtures. Also, note if lenses should be cleaned.
- Verify the operation of the lighting controls for the different ranges of nighttime and daylight illumination.

Lighting Fixtures

Lighting fixtures include mounting brackets, luminaires, and attachments. These should be watertight, dust-tight, and bug-tight for proper operation and easy maintenance. Tunnels are washed periodically to maintain reflectivity, so check the effectiveness of the washing process and any impact on the lighting fixtures. Observe the general condition of the lenses and housing of the lighting luminaires. Note the percentage of clean, broken lenses or housings, and corroded surfaces.

When inspecting lighting luminaires and their attachments, the inspector should look for corrosion damage from environmental conditions and contact with dissimilar metals. Sites of contact are located between the lighting housing base and luminaire, clips attaching the luminaire to the base, and bolts that hold the base to the substrate.

When two dissimilar metals are placed in a conductive and corrosive solution, touching each other, there will be a flow of electrons (electricity) between them causing corrosion. This form of the corrosion is called Galvanic or Dissimilar Metal/Two-Metal corrosion. In the mated pair, the less corrosion-resistant material (anode) will show increased corrosion and the more resistant material (cathode) will show decreased or no corrosion.

Miscellaneous Lighting System Checks

Although these items may not be specifically reported, it is good practice to perform lighting system checks on all miscellaneous lights, fixtures, and appliances in the equipment rooms, maintenance corridors, plenums, ancillary buildings, and auxiliary structures. These items should be included in the owner-defined elements.

Emergency Lighting Systems and Fixtures

These systems provide egress lighting for safe evacuation and must operate in the event of a power failure in the electric grid. These lights are powered by the emergency power distribution system. Inspect emergency lighting systems as previously described when the main source of power has been turned off and the emergency generating system is in operation. The lighting diagrams and electrical schematics should be adequately reviewed prior to conducting field tests.

Inspection of Fire Detection and Life Safety Systems

Fire and life safety and emergency systems are complex interconnected systems. Before conducting an inspection, the design and as-built records should be carefully reviewed along with the vendor-supplied information. For these systems, the general condition of the system components should be assessed along with the state of general housekeeping. Observe the general condition of the equipment and the enclosures, including cabinets and panels. Access panels, doors, seals, and latches should be checked for rusted, deteriorated, broken, or damaged components.

Fire Systems

Fire systems can be categorized into those that alert and detect and those that protect. NFPA produced several useful documents for maintaining, inspecting, and testing fire systems. These include NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways; NFPA 70, National Electric Code; NFPA 72: National Fire Alarm and Signaling Code; NFPA 101, Life Safety Code; NFPA 110, Standard for Emergency and Standby Power Systems; and NFPA 111, Standard on Stored Electrical Energy Emergency and Standby Power Systems. Review the fire and life safety requirements established by the agency having jurisdictional authority, which varies by location. Generally, this is a written agreement between the State DOT, the state fire marshal, and the local fire department. It is good practice to reference and summarize the requirements in the inspection documentation.

Maintenance logs that document system checks should be reviewed before conducting an inspection. Deficiencies in the logbook should be noted. When inspecting fire systems, it is good practice to be on the lookout for unprotected electric wires, improper storage of flammable materials, and products that produce toxic chemicals (e.g., plastics such as PVC or HDPE materials) when burned.

Fire Detection

Fire detection systems are the elements that detect and initiate the response to a fire, such as fire alarms, manual fire alarm pull-boxes, heat detectors, smoke detectors, CCTV, and other types of surveillance equipment. The major components of a fire detection system include control panels, power supplies, detection devices, and notification devices (e.g., alarms). The fire detection system should meet or exceed the design requirements.

NFPA 72, National Fire Alarm Code provides information on inspecting and testing fire alarms and signaling devices. The following recommendations should be considered:

- Inspect the fire detection system by operating the drill switch and ensuring that all of the annunciators and notification appliances are operable.
- Check existing records to determine if the system has been tested at regular intervals in accordance with NFPA 72. Review the last seven years of records.
- Review the system's maintenance/inspection records and note any unusual maintenance issues.
- Note the physical condition of the fire protection system. This includes the fire extinguishers, hose connections, pumping systems, piping, circulating pumps, and hose reels.
- Note the physical condition of the fire protection storage tanks, alarms, and level switches.
- Check the fire control panel for faulty detectors, signals, and wiring.
- Check door sensors and other security measures for proper operation and condition.
- Note any ventilation testing performed or exercises with local responders.

Fire Protection

Fire protection systems are the elements that suppress the fire, enhance tenability, and aid rescue. Fire protection systems include fire extinguishers, standpipes, hoses, nozzles, fire suppression system components (i.e., sprinklers, foam systems, pumps, tanks, heaters), and ventilation control. Small fires can be controlled with powder or foam extinguishers, and most motorists likely know how to use these devices. Check that fire extinguishers are in place and that the expiration date, pressure, and seal are present on portable fire extinguishers. A fire suppression system, such as a sprinkler system, is an active fire protection measure with a water supply system that provides an appropriate pressure and flow rate to water distribution piping and sprinkler attachments that spray water onto the fire. There are variations in these systems, including deluge systems, foam systems, and mist systems.

Proper inspection of these systems requires familiarity with NFPA 25, Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems and other applicable NFPA standards. Local codes may require inspection and commissioning by the fire department or other qualified fire system inspectors.

Inspection of Tunnel Security and Operation Systems

The systems included under security and operation involve surveillance, control, and communication equipment, such as CCTV cameras, telephones, radios, incident response and detection devices, air quality monitors, the control center and systems, and the Supervisory Control and Data Acquisition (SCADA) system.

Inspecting the tunnel security and operation systems should include visual observations and measurements specific to each component. The inspector should:

- Verify that CCTV cameras, telephones, radios, or other communication devices are operational.
- Inspect traffic signals for proper operation during all phases.
- Verify that over-height detector systems are not triggering at any height just below the desired setting and are triggering at or just above the desired setting.

SCADA

The SCADA system operates using signals over communication channels that provide control of remote equipment. The control systems are combined with a data acquisition system that can be programmed to operate the tunnel facility at optimum levels. SCADA systems operate with a minimal amount of hardware maintenance, except for the component level sensors. Software changes for additional programming and periodic upgrades are required to maintain flexibility and reliability of system operation.

Tunnel Security Systems

Tunnel operations and security systems consist of communication equipment (e.g., CCTV cameras, telephones, radios) and various detection equipment. The tunnel operations and security system may also include subcomponents such as closed-circuit camera system, cell phone antennas, door access, controller, and radio.

The requirements for tunnel security should be established by the tunnel owner. A tunnel specific vulnerability assessment is a valuable tool for determining the security needs of the tunnel. Each tunnel facility typically develops its own set of security requirements based on security protocols and policies established by the tunnel owner.

Emergency Communication Systems

Emergency communication systems are integral to fire and life safety systems and tunnel security systems. The components of the emergency communication system include cameras and camera systems (CCTV), intercom, radios, cellphones, receivers, wiring, computer analytics, and other technology. Inspection requires testing the communication devices in simulated emergency conditions. This requires examining issues such as system interoperability, scenario-based exercises for different emergencies and conditions, interagency cooperation for response, and cyber-security. The inspection also includes a visual and technical examination of hardware by specialists.

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East Building
1200 New Jersey Avenue, SE
Washington, DC 20590
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