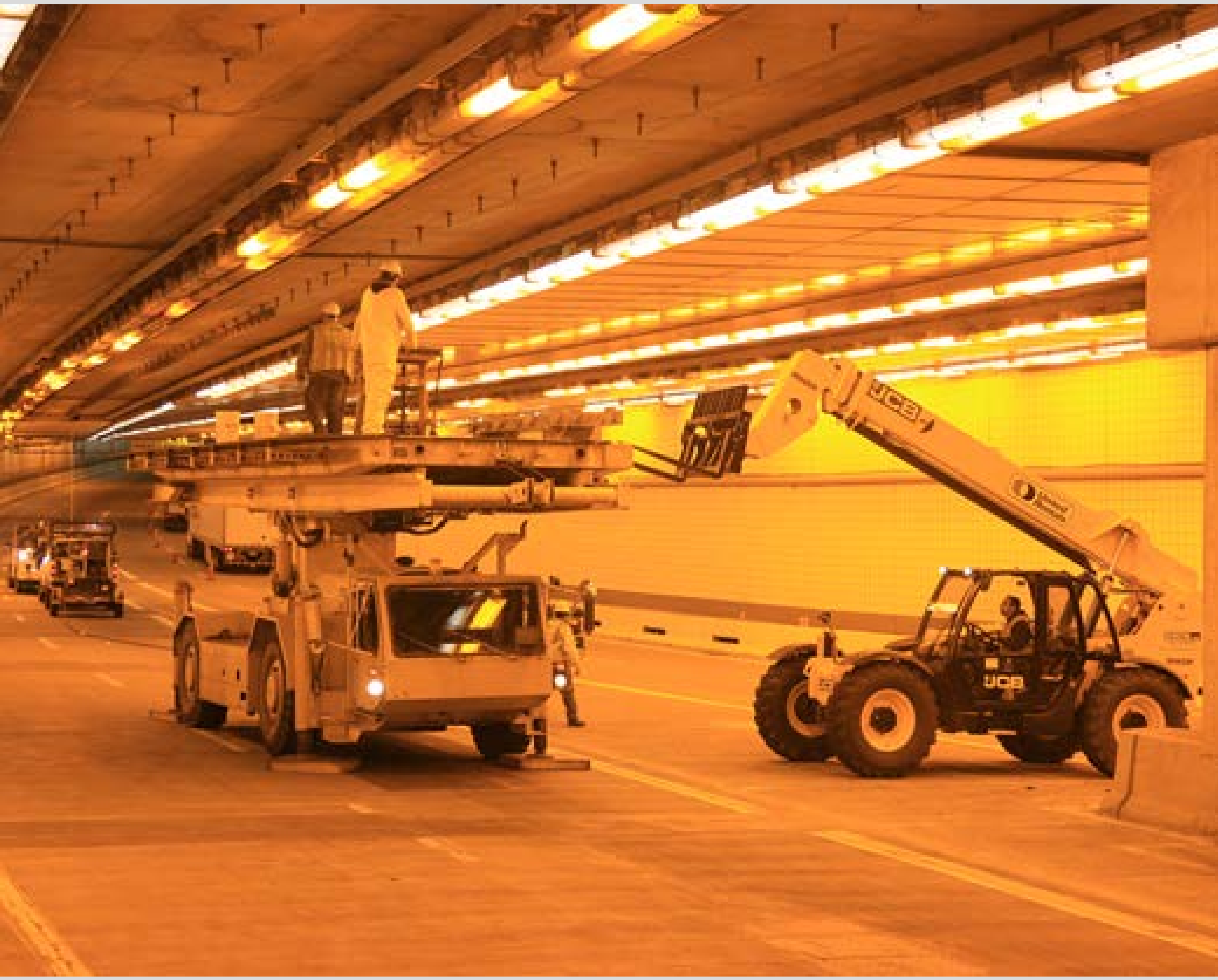




Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual



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16. Abstract

Tunnels represent a significant financial investment with challenging design, construction, and operational issues. Tunnels that are not adequately maintained usually require more costly and extensive repairs. To help safeguard tunnel users and to ensure reliable levels of service, the FHWA developed the National Tunnel Inspection Standards (NTIS), the Tunnel Operations Maintenance Inspection and Evaluation (TOMIE) Manual, and the Specifications for National Tunnel Inventory (SNTI). In accordance with the NTIS, this Manual describes methods for improving the safety and performance of roadway tunnel operation, maintenance, inspection, and evaluation programs.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		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
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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TOMIE MANUAL

CHAPTER 1

INTRODUCTION

Chapter 1 – Tunnels

1 Introduction

The purpose of this manual is to improve the safety and performance of the Nation's highway tunnels. Tunnels are integral to the system of public roads, vital to the economy, and critical to improve mobility for all. This manual provides guidelines on tunnel operations, maintenance, inspection, and evaluation that help ensure tunnels remain in safe condition and continue to provide reliable levels of service. Communities often bear significant social, economic, and environmental costs because of loss of service and rerouted traffic. Lengthy detours from tunnel closures can cause significant social, economic, and environmental hardships on nearby communities because of traffic detours, rerouting of hazardous cargo through neighborhoods, and ensuing gridlock, noise and pollution.

Many tunnels in the United States were constructed in two distinct periods of highway expansion. The first period took place during the 1930s and 1940s as part of the Great Depression era public works programs. The second expansion period occurred during the development of the Interstate Highway System throughout the 1950s and 1960s. The tunnels that were built during these periods are now more than 50 years old, and many have exceeded their intended design service life. Based on preliminary information obtained from an initial tunnel inventory conducted jointly by both the Federal Highway Administration (FHWA) and the Federal Transit Administration (FTA), more than 350 highway tunnels have been identified in the United States. About 40% percent of these tunnels are now more than 50 years old; and approximately 5 percent of these tunnels already exceed 100 years of service. Age and increasing tunnel traffic are among the factors that demonstrate the need for routine inspections to help ensure that tunnels on public roads remain in safe condition and provide reliable service.

Tunnels represent significant financial investments with challenging design, construction, and operational issues. Tunnels remain in service for extended periods of time, sometime beyond their intended service life. Tunnels that are not adequately maintained usually need more costly and extensive repairs. Structural, civil, and functional systems deteriorate at accelerated levels because of the harsh tunnel environment. Many tunnels have complicated functional systems such as lighting, ventilation, drainage, fire detection and alarms, fire suppression, communication and traffic control; these systems must be kept in good working order to minimize death and injury during an emergency such as a vehicle collision, fire, flood, earthquake, or criminal act.

To help safeguard tunnels and ensure reliable levels of service on public roads, the FHWA developed the National Tunnel Inspection Standards (NTIS), the Tunnel Operations Maintenance Inspection and Evaluation (TOMIE) Manual, and the Specifications for National Tunnel Inventory (SNTI). The NTIS contains the regulatory requirements for the tunnel inventory and inspection program; the TOMIE Manual and the SNTI have been incorporated into the NTIS to expand upon these requirements. The TOMIE provides uniform and consistent guidance on the operation, maintenance, inspection, and evaluation of tunnels. The SNTI contains instructions for submitting the inventory and inspection data to the FHWA. The data produced in accordance with these documents will be maintained in the National Tunnel Inventory (NTI) database.

1.1 Overview of the TOMIE Manual

This manual is intended to serve as a resource in the areas of tunnel operations, maintenance, inspection, and evaluation.

- Chapter 1 provides background information on the NTIS, tunnel fundamentals, and an overview of the TOMIE Manual.
- Chapter 2 discusses the operational aspects of highway tunnels, including typical staffing duties.
- Chapter 3 discusses many common maintenance and repair issues for highway tunnels.
- Chapter 4 provides information and guidelines for developing a comprehensive tunnel inspection program.
- Chapter 5 presents evaluation techniques and guidelines for the load rating of highway tunnels.

1.1.1 **Scope and Purpose**

The goal of the TOMIE Manual is to provide uniform and consistent guidance on tunnel operations, maintenance, inspection and evaluation. The manual is intended to serve as a resource for management, stewardship and oversight of key infrastructure investments; and it promotes safe and efficient practices. The NTIS contains the regulatory requirements for the national tunnel inventory and inspection program; the TOMIE and the SNTI are incorporated into the NTIS and expand upon the requirements. The TOMIE discusses the collection of inspection data on highway tunnels, which can be incorporated into a risk-based tunnel management system administered by the tunnel owner to make informed investment decisions.

1.2 Background for the Tunnel Inspection Program

The Moving Ahead for Progress in the 21st Century Act (MAP-21) passed by Congress and signed by the President on July 6, 2012, recognized that the safety and security of the Nation's highway tunnels is of paramount importance. The FHWA developed the NTIS, TOMIE, SNTI, and NTI as an extension of these principles to ensure that tunnels continue to provide safe, reliable, and efficient levels of service for the traveling public. The successful implementation of the past bridge inspection programs and tunnel research efforts led to the development of the new tunnel inventory and inspection program.

1.2.1 **National Bridge Inspection Standards (NBIS)**

Following the Silver Bridge collapse in mid-December of 1967, Congress passed the Federal-Aid Highway Act of 1968, which set forth requirements for establishing the National Bridge Inspection Standards (NBIS). The NBIS was implemented to ensure that highway bridges receive periodic inspection and continue to provide safe, reliable, and efficient service. The NBIS addressed a number of issues including uniform inspection procedures and techniques, personnel qualification, inspection frequency, and the reporting of findings. Following the issuance of the NBIS, the FHWA developed a manual and comprehensive bridge inspection training course. The NBIS also established the basis for the load rating of bridges. The inventory and inspection program developed for highway tunnels was heavily modeled on the success of the NBIS program.

1.2.2 **National Tunnel Inspection Standards (NTIS)**

Tunnels were not addressed in the NBIS or the related bridge inspection manuals and training. In

2008, the FHWA initiated steps to implement the National Tunnel Inspection Standards (NTIS). The process began with the publication of the Advanced Notice of Proposed Rule-Making (ANPRM). After addressing the comments received on the ANPRM, a Notice of Proposed Rule-Making was developed and then published in 2010; however, prior to completing the rule making process in 2012, MAP-21 was signed into law. This new highway law contained a number of tunnel inventory and inspection provisions which needed to be addressed. In July of 2013, the FHWA issued a Supplementary Notice of Proposed Rule-Making (SNPRM) to incorporate the new provisions and to seek comments. The final rule addressed the comments on the SNPRM. When published in the Office of the Federal Register in 2015, the NTIS will become part of the Code of Federal Regulations – 23 CFR Part 650 Subpart E.

The effective date for the NTIS is 30 days after publication. Once effective, the requirements begin for all tunnels on public roads, on and off Federal-aid highways. The intent of the new highway regulation is to establish a basis for uniform and consistent inventory and inspection procedures for all tunnels located on public roads. Under the NTIS, critical findings are to be reported to the FHWA and corrected in a timely manner. The mandate calls for a national tunnel inventory and inspection program, training for tunnel inspectors, and a national certification program for tunnel inspectors.

In association with the National Highway Institute (NHI), the FHWA developed a comprehensive training course that provides national certification for tunnel inspectors. Key inspection personnel, including the program manager and team leaders, are required to become nationally certified tunnel inspectors. The NTIS also permits training, which has been developed by the State and approved by the FHWA, to be substituted for this certification purpose.

The NTIS defines a tunnel as: “an enclosed roadway for motor vehicle traffic with vehicle access limited to portals, regardless of type of structure or method of construction, that requires, based on the owner’s determination, special design considerations to include lighting, ventilation, fire protection systems, and emergency egress capacity. The term "tunnel" does not include bridges or culverts inspected under the National Bridge Inspection Standards (23 CFR 650 Subpart C—National Bridge Inspection Standards).” This definition is consistent with the definition used by the American Association of State Highway and Transportation Officials (AASHTO); and it is intended to capture the structures targeted by this new regulation.

1.2.3 **National Tunnel Inventory (NTI)**

In order to track the conditions of tunnels throughout the United States and to ensure compliance with the NTIS, the FHWA established a NTI database to contain all of the initial tunnel inventory and inspection data. The inventory and inspection data will be available in the annual report to Congress. This data will also allow patterns of tunnel deficiencies to be identified and tracked, which will help to ensure public safety. The NTI database provides information for a data-driven, risk-based approach to asset management that can be used for informed investment decisions.

1.2.4 **Specifications for the National Tunnel Inventory (SNTI)**

The SNTI contains the coding requirements for the tunnel inspection program. The SNTI is used with the TOMIE Manual to inspect and collect data on highway tunnels. The data submitted to the FHWA must be formatted in accordance with the instructions contained in the SNTI instructions. The tunnel inventory and inspection data will be maintained in the NTI database.

1.2.4.1 **Tunnel Inventory**

The SNTI is used to collect the tunnel inventory items such as tunnel identification, age and level of service, classification, geometric data, inspection, load rating and postings, navigation, and structure type. The SNTI inventory items require the following information: the item name, specification, commentary, examples, format, and the alpha-numeric identification. The specification contains descriptions of each inventory item; and it provides a series of explanations in the commentary section. Example items are also provided to demonstrate "how to" coding information for various situations.

1.2.4.2 **Tunnel Inspection**

The SNTI is used with the TOMIE to collect comprehensive tunnel inspection data on the structural, civil, and functional systems within the tunnel. Functional systems include mechanical systems, electrical systems, lighting systems, fire life safety and security systems, signs and protective systems. There are two main tables that provide element level coding instructions. The first table has five parts: the element name, unit of measure, element number, specification, and commentary. The second table lists the four condition states.

1.3 Tunnel Owner Resources and Guidelines

The tunnel inventory and inspection program is built upon previous developments in highway and rail tunnel applications. The FHWA and FTA cosponsored an initiative for initial inspection, maintenance, rehabilitation, and management of transportation tunnels

1.3.1 **Tunnel Inspection, Maintenance, Rehabilitation, and Management**

Because of their common interest in transportation tunnels, the FHWA and FTA joined efforts in March of 2001 to cosponsor the initiation of a tunnel management system for highway and transit facilities. As part of this effort, an informal inventory of highway and transit tunnels was completed. An inspection manual, maintenance, and repair manual, and a data management program for tunnels were also developed.

1.3.1.1 **Highway and Rail Transit Tunnel Inspection**

The *Highway and Rail Transit Tunnel Inspection Manual*, 2005 Edition (HRTTIM) was developed jointly by FHWA and FTA to address inspection procedures for civil, structural, and functional systems within highway and transit tunnels. The manual provides guidance on inspection, documentation, and explains the priority classification of defects.

(http://www.fhwa.dot.gov/bridge/tunnel/inspectman.pdf)

1.3.1.2 **Highway and Rail Transit Tunnel Maintenance and Rehabilitation**

The *Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual*, 2005 Edition (HRTTMRM) was developed by FHWA/FTA to address maintenance and repair practices on civil, structural, and functional systems of highway and rail transit tunnels. This manual provides information on the maintenance and rehabilitation of highway and transit tunnels.

(http://www.fhwa.dot.gov/bridge/tunnel/maintman00.cfm)

1.3.1.3 **Tunnel Management System (TMS)**

The FHWA and FTA recognized the importance of a comprehensive data management system for tunnels and circulated an informal survey to 45 highway tunnel owners from which there were 40 respondents. Similarly rail transit organizations were contacted. The preliminary survey suggested that there are roughly 350 U.S. highway tunnels within the United States. The responses also indicated that tunnels have been inspected by their owners at intervals ranging from 1 day to 10 years with the average interval around 24 months.

1.3.2 **FHWA Technical Advisories**

As part of its responsibilities, the FHWA has issued Technical Advisories in response to various incidents or events. In 2006, the FHWA performed extensive tests on “Fast Set epoxy” that was used to anchor suspension rods of ceiling panels. Technical Advisory T 5140.26 (now superseded by T 5140.30) was issued shortly after this investigation. The advisory recommends that “Fast Set epoxy” not be used for adhesive anchor applications because of long term creep issues, and where the epoxy had already been used for sustained tension applications, it recommends that the components be retrofitted using mechanical anchorages.

1.3.3 **AASHTO SCOBS Technical Committee on Tunnels (T-20)**

The AASHTO Subcommittee of Bridges and Structures (SCOBS) Technical Committee on Tunnels (T-20) is responsible for identifying tunnel research needs such as those from the National Cooperative Highway Research Program (NCHRP) and for disseminating state-of-the-art information and practices on highway tunnels.; T-20 members have been involved in the review of the tunnel inventory and inspection documents developed by the FHWA.

(http://bridges.transportation.org/Pages/T-20Tunnels.aspx)

1.3.3.1 **Best Practices for Tunnel Inspection QC/QA**

NCHRP executed Project 20-07/Task 261, *Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspection.* This 2009 AASHTO report summarizes current inspection practices for 32 highway and 11 transit tunnel owners. The report compiled information on inspection stages, procedures, and inspector qualifications. Best practices were also included for safety and emergency response system testing.

(http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(261)_FR.pdf)

1.3.3.2 **Rehabilitation of Existing Tunnels (Guidelines)**

NCHRP executed Project 20-07/Task 276, *Development of Guidelines for Rehabilitation of Existing Highway and Rail Transit Tunnels*. These guidelines were published in July 2010 to establish best practices for the repair of existing tunnel elements. The report focuses on structural and drainage repairs and provides detailed recommendations on the steps of the rehabilitation process.

(http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(276)_FR.pdf)

1.3.4 **TRB AFF60 – Committee on Tunnels and Underground Structures**

The Transportation Research Board (TRB) Committee on Tunnels and Underground Structures (AFF60) focuses on the design and construction of underground transportation projects and their system components.

(http://www.personal.psu.edu/jur17/AFF-060/)

1.3.5 **Tunnel Scan Executive Summaries**

The FHWA, AASHTO and NCHRP have jointly sponsored two tunnel scans to learn more about the innovative practices used internationally and domestically for tunnel design, construction, operation, and emergency management. The scanning teams consisted of representatives from FHWA, State departments of transportation, a transit agency, a turnpike authority, and a tunnel consultant.

1.3.5.1 **European Scan**

In June 2006, the FHWA organized a field survey of several tunnels in Europe to learn more about the design and operation philosophies used with international tunnel applications. Several innovative design and emergency management plans were evaluated. As a result of this European scan, the field team made the following nine recommendations for tunnels:

1. Develop universal, consistent, and more effective visual, audible, and tactile signs for escape routes.
2. Develop AASHTO design and operation guidelines for existing and new tunnels.
3. Conduct research and develop guidelines on tunnel emergency management that includes human factors.
4. Develop education for motorist response to tunnel incidents.
5. Evaluate effectiveness of automatic incident detection systems and intelligent video for tunnels.
6. Develop tunnel facility design criteria to promote optimal driver performance and response to incidents.
7. Investigate one-button systems to initiate emergency response and automated sensor systems to determine response.
8. Use risk-management approach for tunnel safety inspection and maintenance.
9. Implement light-emitting diode lighting for safe vehicle distance and edge delineation in tunnels.

(http://international.fhwa.dot.gov/uts/)

1.3.5.2 **Domestic Scan**

Similar to the European scan, a survey was performed in August 2009 of several significant U.S. tunnels. The goal of this survey was to determine the best practices for roadway tunnel design, construction, maintenance, inspection, and operations. The scan team investigated tunnels on the state, regional, and local highway systems. As a result of this two month survey, the following eight recommendations were made:

1. Develop standards, guidance, and best practices for roadway tunnels.
2. Develop an emergency response system plan unique to each tunnel facility which takes into account human behavior, facility ventilation, and fire mitigation.
3. Develop and share inspection practices among tunnel owners.
4. Consider inspection and maintenance operations during the design stage.
5. Develop site-specific plans for the safe and efficient operation of roadway tunnels.

6. A tunnel includes a long-term commitment to provide funding for preventive maintenance, upgrading of systems, and training and retention of operators.
7. Share existing technical tunnel design knowledge within the industry.
8. Provide education and training in tunnel design and construction.

(http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_09-05.pdf)

1.4 Fundamentals of Highway Tunnels

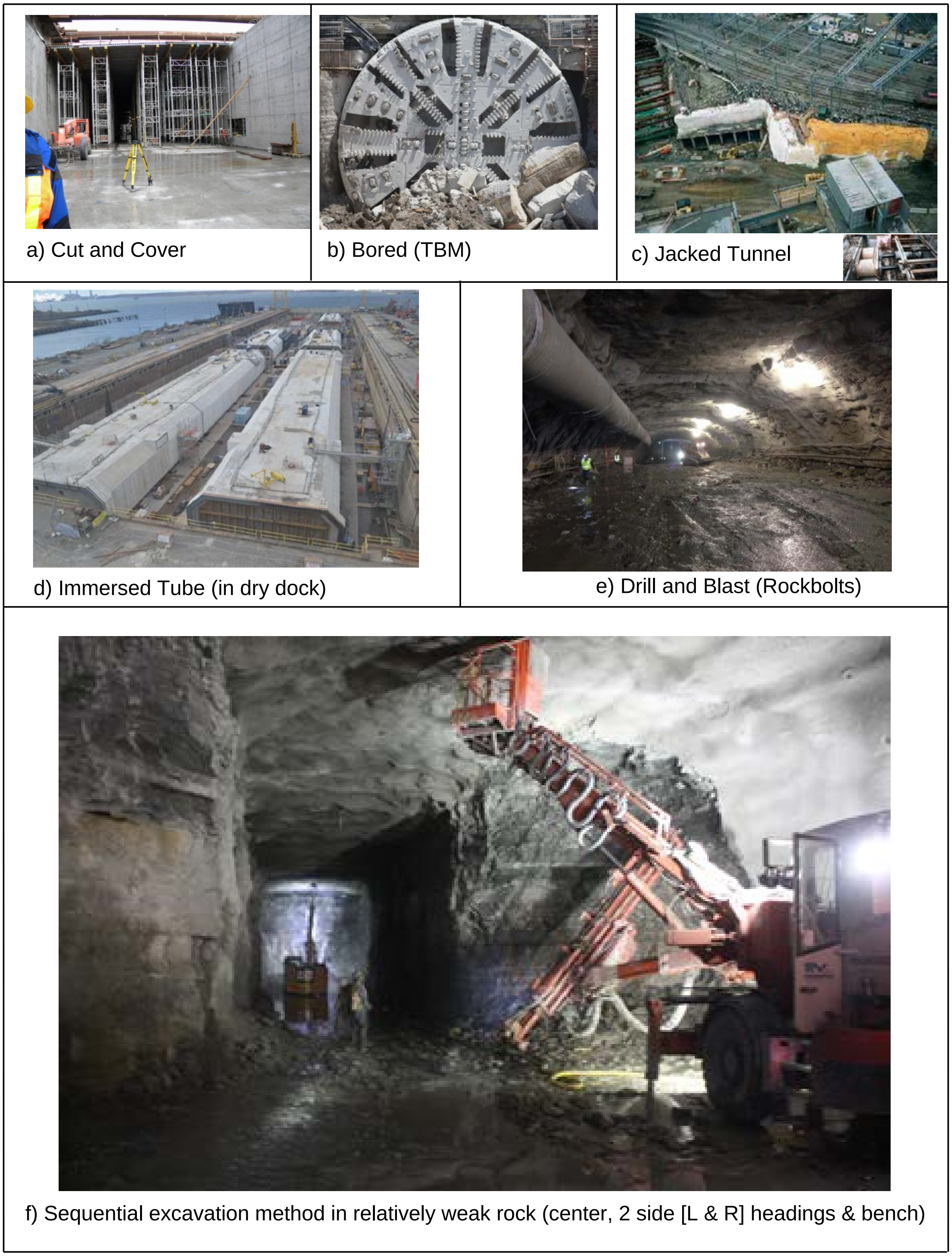
It is important to have a basic understanding of U.S. highway tunnel construction methods, shapes, liner types, invert types, and tunnel finishes. In general, the shape of a tunnel is related to the method of construction, which is based on ground conditions and other project specific requirements.

1.4.1 Construction Methods

Tunnel construction methods and ground conditions influence the shape of the tunnel. There is usually an optimum tunnel construction method for a given set of project conditions. The subsurface conditions play a large role in deciding what tunnel construction method to implement; however, there are other project specific factors that must be considered before making the final selection. The common types of construction methods include cut and cover, shield driven, bored, jacked, immersed tube, drill and blast, and sequential excavation. Table 1-1 summarizes the relationship between construction method and typical shape.

Table 1-1 – Construction methods versus typical shape.

Construction Method	Circular	Rectangular	Horseshoe	Oval
Cut and Cover		X		
Shield Driven	X	X		
Immersed Tube		X		
Drill and Blast			X	X
Sequential Excavation			X	X



a) Cut and Cover

b) Bored (TBM)

c) Jacked Tunnel

d) Immersed Tube (in dry dock)

e) Drill and Blast (Rockbolts)

f) Sequential excavation method in relatively weak rock (center, 2 side [L & R] headings & bench)

Figure 1.1 – Typical construction methods and general shapes for highway tunnels.

1.4.1.1 **Cut and Cover**

Cut-and-cover tunnel construction typically involves digging a trench, building the tunnel structure within the trench, and covering it up with an engineered backfill material. Since these tunnels are dug from the ground surface, they are more economical when located at shallow depths. This method is usually not feasible for crossing streams, mountains, or major transportation corridors; digging from the surface also presents challenges when buried utilities are present.

Typically, cut-and-cover tunnel structures are constructed using cast-in-place concrete liners that are box-shaped. The temporary shoring for this type of construction generally consists of soldier piles and lagging, sheetpile walls, or slurry walls. Internal bracing or tiebacks are normally required to support the temporary walls during construction. When there is enough space available, the sidewalls of the excavation can be sloped instead of using the bracing. In some cases, piles are driven along the edges of the open trench to provide support for the tunnel and help prevent the structure from settling. Trusses and beams are used to build the structural framework. After the appropriate reinforcing is placed within the forms, the invert, walls, and roof are typically cast-in-place. The roadway is constructed within the footprint of the excavation; and the structure is fitted with pipes, conduits, and other utilities, as necessary. Figure 1.1.a shows a series of photos to illustrate this construction method.

1.4.1.2 **Shield Driven**

Shield driven tunnels are used when the ground needs to be controlled or otherwise supported during the excavation process. Closed shields are used when groundwater control is necessary. With this method, a shield is advanced one cycle at a time typically while removing the muck and placing the ground support concurrent to the face. This process is then repeated as often as necessary to complete the tunnel. Specialized applications of the shield driven tunnel include use of tunnel boring machines and jacked tunnels Shield driven tunnels can be round or rectangular depending on the cross-section shape of the shield, and the procedure used to excavate the tunnel. Typically, the full-face of the heading is excavated before advancing the shield.

1.4.1.3 **Bored Tunnels**

A Tunnel Boring Machine (TBM) is a shield with bits mounted on a rotating cutter head that excavates a circular opening. Ground characteristics have a significant influence on the selection of the tools and the configuration of the machine. Some TBMs allow for limited interventions at the cutting face to replace the cutting tools. These interventions may involve compressed air, termed hyperbaric interventions, to stabilize the ground at the excavated face. In general, most interventions are planned to take place at geologically favorable locations along the alignment to minimize the risks to personnel and to manage production costs. Some of the modern TBM's allow the cutting tools to be replaced from within the safety of the machine; however, this has tradeoffs because the cutting tools are very difficult to handle within these tight spaces. TBMs are considered to be more cost effective on longer tunnels where economies of scale allow the cost of the machine to be recovered. Figure 1.1.b depicts a photo of a TBM at tunnel breakthrough. After the job, the TBM may have resale value.

Figure 1.2 – TBM using large hydraulic jacks to advance against assembled segment ring.

Soft ground – In typical soft ground applications, the TBM is designed to balance the ground and groundwater pressures at the excavated face, which helps to minimize ground loss, settlement, and potential damage to structures, utilities, and roads. Closed face machines are sealed, except at ports controlled by the TBM operator, to prevent both groundwater and unconsolidated ground from entering the shield at the excavated face. Slurry or soil conditioning allows the TBM operator to balance the face pressures and limit settlement. To limit ground loss, the excavation rate is synchronized with the advance rate of the machine; and as the machine advances, a proportional amount of soil is removed at the excavated face. The ground is supported by the shield until precast segments can be erected within the tail shield. Since, the TBM and tail shield is slightly larger in diameter than the assembled ring, the small space or annulus between the tail shield and ring should be immediate filled to minimize the potential for settlement. As the machine is advanced (See Figure 1.2), grout is pumped into the annulus to fill this void. The TBM is advanced by large hydraulic jacks that thrust against the rings of assembled precast liner segments.

Hard rock – In hard rock applications, the TBMs are designed to rapidly cut through the rock mass. The TBMs are generally not designed to control the ground or groundwater to the same extent as a closed face machine since hard rock excavations are generally relatively stable and fairly watertight. These open faced machines do not need to be equipped with complicated mechanisms to control ground loss and settlement, which would tend to slow down the rate of production as well as add significant cost to the machine. Fracturing, jointing, and faulting can be detected ahead of the TBM by probe hole drilling in advance of the excavated face. When undesirable conditions are encountered in the probe holes, the area ahead of the excavation can be grouted and improved. In many hard rock excavations, the TBM can be efficiently advanced by grippers that thrust against the hard walls of the rock mass. Rock bolts and other types of rock support are installed behind the machine, as necessary, to stabilize the opening. After the tunnel is bored, a cast-in-place final liner is usually installed.

1.4.1.4 **Jacked Tunnels**

Obstructions such as highways, buildings, and rail lines can preclude surface excavation methods such as cut and cover techniques. Tunnel jacking is considered to be a relatively non-intrusive method of constructing tunnels. The headings are advanced by pushing large concrete box sections through the soil typically crossing under structures and transportation routes where settlement is of primary concern. Grouting or freezing can be used to help stabilize the soils around the tunnel opening; however when freezing is used, long-term settlement may result as the ground thaws over the many years that follow. Large hydraulic jacks push the precast tunnel sections into place from a launching pit while the ground at the face is simultaneously excavated. At the end of the cycle, the jacks are retracted; a new segment is added at the launching pit; and the string of segments is gradually pushed into place to advance another cycle. This process is repeated as often as necessary to complete the tunnel from the launching pit to the receiving pit. Very large friction forces can be generated when this method is used since the string of assembled sections becomes longer with each additional cycle. Figure 1.1.c shown enlarged in Figure 1.3 depicts a photo taken during a jacked tunnel operation that used ground freezing techniques.

Figure 1.3 – Jacked tunnel advancing under rail corridor.

1.4.1.5 **Immersed Tube**

A body of water such as a canal, channel, bay, or river can be crossed using immersed tube tunnel technology. In past U.S. Practice, this technology made use of steel shells cast with mass concrete. Many modern applications make use of massive precast concrete elements that focus on concrete mix design in an attempt to control thermal strains and cracking during the fabrication process. Cost considerations, durability requirements, and constructability issues are the primary factors that drive the decision making process. The thermal heating and cooling effects must be considered when working with mass concrete pours with respect to the water-tightness of the structure.

With precast concrete elements, a litter of about six to eight tunnel elements can generally be constructed within a dry dock over a period of about a year. As an example of scale, one of these individual tunnel elements might incorporate 12,000 tons of concrete and 1,000 tons of steel reinforcing. Sometimes more than one litter of elements is needed to complete the length of the tunnel. Each segment is individually designed to fit into the alignment, which usually slopes from each end towards the middle where the drainage is collected. The ends of each segment are bulk-headed while in the dry dock to make them relatively watertight. If cracking of the concrete is a problem, a waterproof coating can be applied to the concrete surface.

Concurrently with segment fabrication, the sand bed foundation is readied using a screed barge that carefully prepares the tunnel alignment under the water surface where the segments will rest. While the sand bed foundation is prepared and after the liter has been fabricated, the dry dock is flooded with water, and the watertight elements float just a few feet above the water surface. Then, tugboats attach to these elements and tow them to the tunnel site. Once the segments positioned above the alignment, they are immersed to grade and fitted against the preceding tunnel element. When the bulkhead between the two elements is drained of incompressible water, the segment moves forward slightly and compresses a specialized gasket since one end of the segment is still exposed to external hydrostatic water pressure. This “Gina” gasket, located between the segments, extends around the perimeter of the tunnel element to form a watertight seal. After placing the elements and installing the tunnel interior finishes, the trench is backfilled with an engineered fill to help protect the tunnel elements from ships, scour, and to resist positive buoyancy. This protective fill must be designed to resist erosion. Figure 1.1.d depicts a progress photo of this construction method.

1.4.1.6 **Drill and Blast**

The drill and blast method has had more than a century of successful implementation. In hard rock tunnels, drill and blast techniques can provide a cost effective solution especially for shorter applications or when the rock mass is subject to variable conditions such as faulting and shear zones. Drill and blast methods may be used in conjunction with sequential excavation methods when developing large span openings in rock or when the quality of the rock is insufficient. These tunnels are usually excavated in a horseshoe shape to provide a supported or reinforced arch over the opening since the main instability occurs in the crown. The sides and invert of the excavations are relatively stable in sound rock formations. When the rock mass is of poorer quality and the stresses are higher, the excavation can be rounded or ovaled to provide arching in the sides and invert.

With drill and blast methods, drill jumbos drill one round into the face of the tunnel, which is typically 5-15 ft. The drill holes are loaded with explosives and detonated. This breaks the rock into smaller fragments, which can be loaded onto vehicles or conveyor belts and removed from the tunnel. A geologist usually monitors the rock conditions at the face, and crew members install the initial support that is needed to stabilize the opening in the rock mass. The initial support generally consists of some combination of rock bolts, dowels, and shotcrete. This process is repeated in cycles as necessary to complete the length of the tunnel. After the tunnel is completed, a cast-in-place final liner is placed. Figure 1.1.e depicts a photo of this construction method.

1.4.1.7 **Sequential Excavation Method (SEM)**

When the ground lacks the strength for full-face excavation, removal can be done in stages. The intermediate stages are supported as necessary, and the next portion is incrementally excavated until the full cross-section is completed. With this method, a geotechnical engineer usually monitors the ground conditions at the face while crew members install the initial support needed to stabilize the opening. This process is referred to as the sequential excavation methods (SEM). Although it is commonly used in soft ground and weak rock, SEM can also be combined with drill and blast methods and used in hard rock applications. This is useful for excavating large underground openings such as a cavern or chamber. With these methods, tunnels are usually constructed in a shape that resembles an egg or oval. Rounded shaped sections are more efficient at accommodating the stresses flow around the opening.

SEM is generally carried out in shorter tunnels; whereas, TBM methods are often more economical for long tunnels. SEM ground support methods are very effective at controlling settlement when tunneling under shallow cover because the support methods for this technique can be easily adapted for this purpose. After the tunnel is completed, a cast-in-place final liner is placed to accommodate the permanent loads. Figure 1.1.f depicts a generalized construction sequence for a tunnel built using SEM in weak rock.

1.4.2 **Tunnel Shapes**

Figure 1.4 to Figure 1.6 illustrates the four common highway tunnel shapes to include circular, rectangular, horseshoe, and oval. Although numerous tunnels have rectangular interiors, the tunnel exterior defines the shape of the tunnel. The exterior shape generally correlates with the method of tunnel construction and the encountered ground conditions. Some tunnels may have different shapes along their length because the ground conditions change along its length. For example, a tunnel could start out using shallow cut and cover techniques leading up to the portals, which are usually constructed rectangular in shape. As these tunnels penetrate deeper into the subsurface and cross under obstacles, other tunneling methods may be used such as sequential excavation, drill and blast, or even TBM methods. The exterior shape usually changes with changes in the tunnel construction method or to accommodate greater stresses at depth.

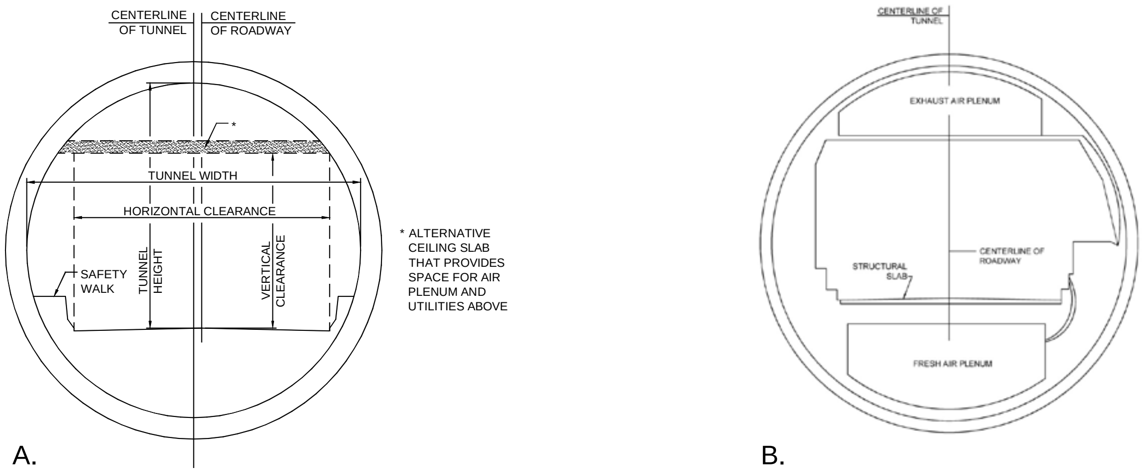


Figure 1.4 – A) Circular tunnel with two traffic lanes and one safety walk with a slab-on-grade. B). Also shown is an alternative ceiling slab. Invert may be solid concrete or a structural slab that provides void space to meet ventilation and/or drainage requirements.

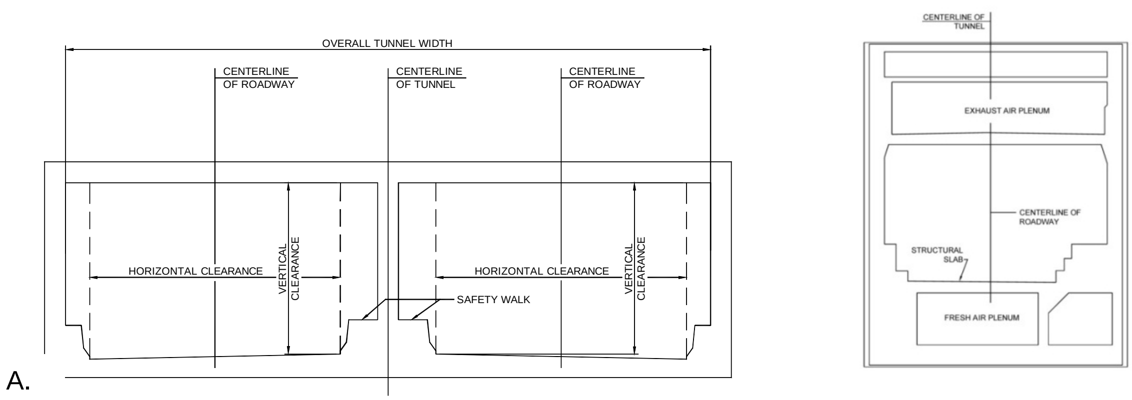


Figure 1.5 – A) Rectangular shaped tunnels. Left shows twin tunnels each with two lanes and one safety walk. The center wall may be solid or built with consecutive columns. B) Right is a box tunnel shown with two traffic lanes and a single safety walk. Invert may be constructed of solid concrete or a structural slab that provides void space for ventilation and/or drainage.

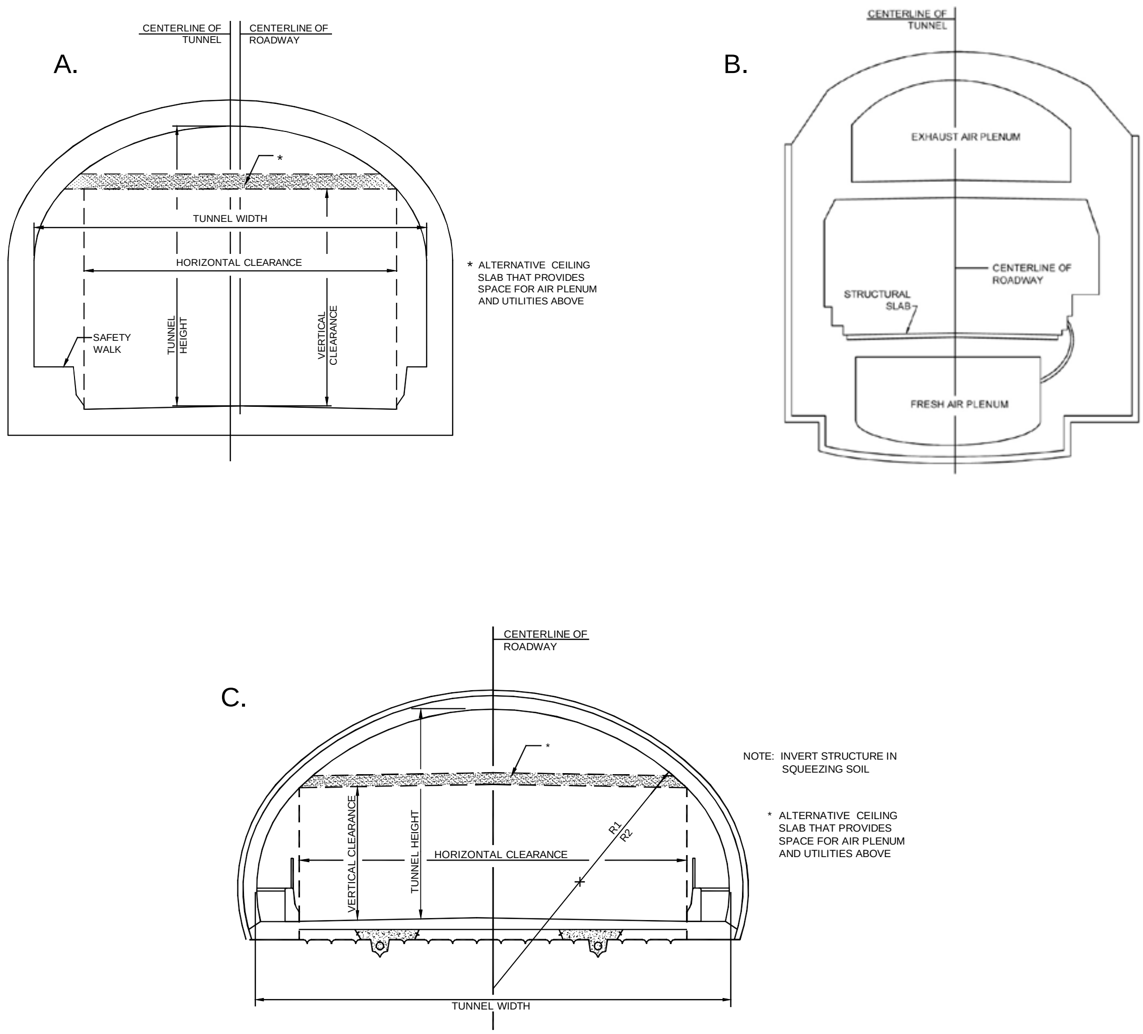


Figure 1.6 – A) Horseshoe tunnel with two traffic lanes and one safety walk. B) Also shown is an alternative ceiling slab. The invert may be solid concrete or a structural slab that provides void space to meet ventilation and/or drainage requirements. C.) Oval tunnel is shown with three traffic lanes and two safety walks. Also shown is alternative ceiling slab. With this approach, the lower portion of the tunnel may be curved to more effectively resist the ground and/or groundwater pressures. The invert may be solid concrete or a structural slab that provides a void space to meet ventilation and/or drainage requirements.

1.4.3 **Liner Types**

Support for the tunnel opening is provided by the liner, which stabilizes the ground around it and resists the infiltration of groundwater. Many tunnels have a two pass liner system made of the initial liner (or temporary support) and the final liner (or permanent support). Initial support is typically provided by shotcrete and rock bolts, ribbed systems with lagging, or slurry walls. The final support is provided by concrete such as cast-in-place liners or precast segments. The type of liner is influenced by the type of construction method used. For example, soft ground TBMs may use precast concrete segments since the machines are advanced by jacking the assembled string of tunnel segments, while hard rock tunnels constructed by TBMs may install cast-in-place concrete final liners because these machines can be advanced by grippers. The basic materials for tunnel lining include cast-in-place concrete, prefabricated concrete, cast iron, and steel. The common methods of support include:

- Unlined rock excavation with rock reinforcement
- Shotcrete
- Ribbed systems and lagging
- Segmental linings/Precast concrete
- Cast-in-place concrete
- Slurry walls

1.4.3.1 **Unlined Tunnels in Rock with Reinforcement As Needed**

Some rock tunnels do not require a liner since these tunnels are self-supporting with the help of localized or systematic rock reinforcing elements (See Figure 1.7). Rock support is used to increase the stability of the rock mass by stitching together structural defects around the excavated opening. For example, when blocks of rock contain joints and fractures, rock reinforcement can be used to lock these blocks of rock into position; a stable compression arch forms above the opening using un-tensioned dowels or tensioned rock bolts. Metal straps, mine ties, welded wire fabric, and shotcrete can be applied to prevent loose rock from spalling between the bolts and dowels. Other supports are installed, as needed, to control the encountered ground and groundwater conditions at localized areas such as the portals, shear zones, and faults. Unlined rock tunnels were common in older mountain rail applications; several of these tunnels have been converted into local access highway tunnels.

Figure 1.7 – Unlined rock tunnel.

1.4.3.2 **Shotcrete**

Shotcrete is pneumatically applied concrete, conveyed through hoses and projected at high velocity onto surfaces. It is reinforced by conventional steel rods, steel mesh, and/or fibers. Shotcrete is used for its ease of application and short curing time. Shotcrete is commonly used as temporary support; however, shotcrete can also be used as the final liner, typically for lightly loaded structures (See Figure 1.8). Shotcrete is sprayed onto the surface in layers to build up the thickness of the liner. The mix can be sprayed either wet or dry; and it can be placed with or without reinforcement. Reinforced shotcrete consists of welded wire fabric or either randomly-oriented fibers of steel or synthetic materials. To cover up any sharp edges from the fibers, a smoothing layer of shotcrete can be applied, for example, to protect the applied waterproofing membrane. The smoothing layer does not contain fibers.

Figure 1.8 – Examples of shotcrete lined tunnels.

1.4.3.3 **Ribbed systems**

Ribbed systems are used in soft ground and rock applications for constructing tunnels and shafts; however, the ribs are usually installed as temporary support as part of a two pass lining process. The first pass consists of installing wood, steel, or shotcrete ribs spaced for the encountered ground conditions. Figure 1.9 depicts wood ribs and lagging on the left and steel ribs and lagging on the right. After the ribs have been installed, lagging is commonly placed between the ribs to help prevent the ground from loosening and unraveling; the lagging also helps to protect workers and equipment from any falling debris. Ideally the lagging is comprised of shotcrete or steel decking material; but timber is commonly used, which can leave voids behind the liner after rotting. The reinforced concrete final liner is then placed during the second pass. The long-term effects of the ribs are generally ignored for stability since they are usually not provided with sufficient corrosion protection to ensure longevity. Lattice girders sprayed with shotcrete can be used to form a rib and lagging system.

Figure 1.9 – Examples of ribs and lagging: wood, left; steel, right.

1.4.3.4 **Segmental linings/Precast concrete**

Precast concrete segments are installed to support the tunnel bore behind the TBM in soft ground and weak rock applications (See Figure 1.10). The TBM advances by thrusting off the completed rings of precast concrete segments, which provide the initial and final ground support as part of a one-pass lining process. The segments are designed to resist the permanent loads from the ground and groundwater as well as the temporary loads from production, transportation and construction. The temporary loads usually govern the design. Tunnel segments are reinforced to resist the tensile stresses at the service level and the ultimate limit states. They are bolted together with gaskets between segments to reduce the amount of water infiltrating through the joints. Concrete segments are also cast with immersed tube tunneling and jacked tunnel applications and transported into place.

Figure 1.10 – Example of precast segmental lining.

1.4.3.5 **Cast-in-place concrete**

Cast-in-place linings are used to provide a durable finish especially for large and complex tunnel structures (See Figure 1.11). Cast-in-place concrete is transported in an unhardened state, primarily as ready-mix, or batched on site, and placed into forms.

Cast-in-place concrete is commonly used as the final lining for a two pass lining system. The concrete is usually reinforced with rebar or welded wire fabric; however, fibers are increasingly being used to provide various levels of reinforcement. Some applications use unreinforced concrete. Concrete is an easy material to work with, and it may be installed over temporary supports, placed against a waterproofing membrane, or used as a non-structural finish for fire proofing and corrosion protection.

Figure 1.11 – Example of cast-in-place concrete liner.

1.4.3.6 **Slurry Walls**

Slurry wall construction types vary depending on project conditions. A common technique is to excavate primary and secondary panels along a trench corresponding with the proposed finished wall configuration. During construction, these panels are filled and maintained with slurry to stabilize their earthen sidewalls. After cleaning the bottom and sides of the panel of loose muck, reinforcing is lowered into the panel. Concrete is then tremie-placed to the bottom of the trench where it displaces the lighter slurry above. The procedure is repeated until a contiguous wall is formed by each of the individual panels. Once the wall panels have been completed, the global excavation commences with the slurry wall acting as the shoring. The slurry wall may be braced using struts, tiebacks or pre-stressing as the excavation proceeds. Slurry wall construction can be used as temporary support, or less commonly, the slurry wall panels can be incorporated into the final structure.

1.4.4 Structural Slabs

Cast-in-place structural slabs and pre-cast panels may be incorporated into the ceiling structure or the invert structure of a tunnel. Slabs and panels are supported by girders or hangers and anchorages while slabs on grade are supported by the ground. When hangers and anchorages are used to support the ceiling structures, the anchorages should be carefully inspected, especially anchors in sustained tension. Epoxy anchors creep; and disastrous consequences have resulted.

1.4.5 Wearing Surface

The wearing surface is the sacrificial portion of the exposed roadway that covers invert slab. The wearing surface helps protect the structural portion of the slab from wear and damage. Wearing surfaces can be anything from a thin layer of concrete (integral wearing surface) to an overlay of latex modified concrete or bituminous asphalt. When making repairs to the wearing surface, it is important to consider the impact on vertical clearances for the traffic using the tunnel.

1.4.6 Internal Walls

Internal walls are sometimes placed in tunnels to separate traffic that is travelling in opposite directions. The internal walls can contain electrical conduit, drainage components, fire suppression and other elements of functional systems. The internal wall may include cross-passageways or serve as a barrier between bores to protect evacuees should emergency conditions develop in the tunnel such as fire and smoke.

1.4.7 Drainage

The tunnel drainage system collects and disposes the water that enters the tunnel. Groundwater infiltrates into the tunnel through cracks in the tunnel lining. Surface waters (including flooding) enter the tunnel through the portals or vent shafts. Furthermore, many tunnels need to be periodically washed as part of a preventative maintenance program. For example, water on the roadway presents hazards such as hydroplaning, engine stalling, or reduced visibility. To mitigate these issues and hazards, tunnel drainage uses grates and inlets to remove water from the roadway into a sump or a drainage system. Once reaching those areas, a tunnel may require pumps, pipes, and, potentially, gates, to properly discharge these waters.

The drainage system collects spilled fuel and oil, which could pose a risk for fire or explosion. It is important to monitor collection points on drainage systems for explosive gas to mitigate any potential hazards from the accumulation of dangerous gasses. Since drainage systems must collect flammable liquids during fire emergencies, the pipes should be noncombustible.

1.4.8 Tunnel Finishes

Ceramic tiles, porcelain enamel, and epoxy coatings are common tunnel finishes. The interior finish of a tunnel is very important to the overall function of the tunnel. To improve safety and facilitate the ease of maintenance, tunnel finishes should:

- Be designed to enhance tunnel lighting and visibility.
- Be fire resistant.
- Not generate toxic fumes during a fire.
- Be able to attenuate noise.
- Be easy to clean.

1.4.9 **Ventilation Systems**

Tunnel ventilation systems operate in normal mode to exhaust fumes produced by motor vehicles and under emergency conditions to remove heat and smoke. Normal mode ventilation systems dilute toxic gasses and pollutants from motor vehicles to maintain safe operations. Emergency tunnel ventilation systems must be able to vent smoke and excessive heat from the tunnel in the event of a fire. The systems should also generate positive air flow to help prevent emergency escape routes from filling with smoke during the evacuation process. Additional information on emergency tunnel ventilation systems can be found in NFPA 502 (National Fire Protection Association). See Reference Section for additional details.

1.4.9.1 **Basic Types of Ventilation Systems**

There are five basic types of tunnel ventilation systems:

- Natural Ventilation
- Longitudinal Ventilation
- Semi-Transverse Ventilation
- Full-Transverse Ventilation
- Single-Point Extraction.

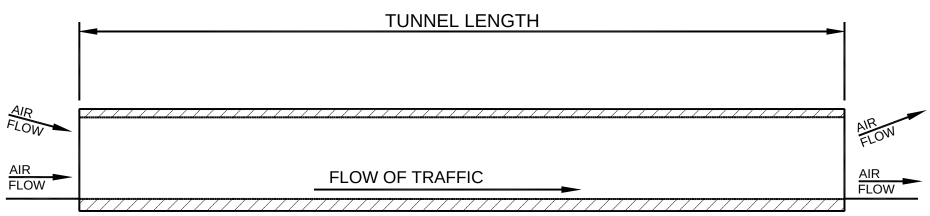


Figure 1.12 – Natural Ventilation.

Natural Ventilation – A naturally ventilated tunnel is simple. The movement of air is controlled only by meteorological conditions and the piston effect from traffic where stale air is pushed out of the tunnel from vehicles traveling through the tunnel in the same direction. This piston effect is reduced when bi-directional traffic is present. The meteorological conditions come from elevation and temperature differences between the two portals and from prevailing winds that channel through the tunnel. Figure 1.12 shows a profile of a naturally ventilated tunnel. Many naturally ventilated tunnels have axial fans installed for fire and smoke emergencies.

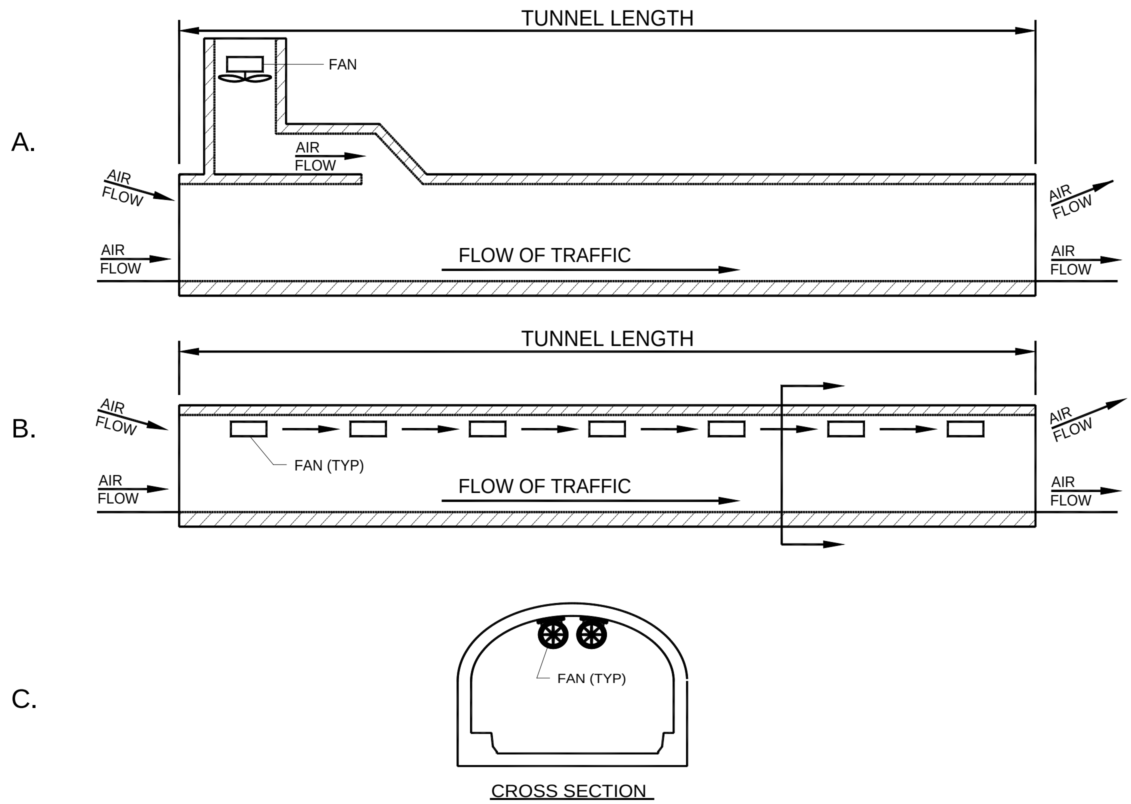


Figure 1.13 – Longitudinal ventilation A) Saccardo nozzle; B) Jet fans; C) Cross section.

Longitudinal Ventilation – Longitudinal ventilation is similar to natural ventilation with the addition of mechanical fans to improve the ventilation characteristics. The air is blown through the tunnel bore, which acts as the ductwork for the fans. The fans can generally be reversible to push air into the tunnel or to pull air from the tunnel. Figure 1.13 shows two different configurations of longitudinally ventilated tunnels.

Semi-Transverse Ventilation – Semi-transverse ventilation also makes use of mechanical fans for the movement of air; however, ductwork is added with flues that allow the air to be uniformly distribution throughout the tunnel. This plenum or ductwork is typically located above a suspended ceiling or below a structural slab within a tunnel. In these systems, air either leaves or enters through the portals while the tunnel bore acts as either the intake or exhaust duct, respectively.

It should be noted that there are many variations of a semi-transverse system. Figure 1.14 shows two examples. The first is an example of a supply-air semi-transverse system; and the second is an example of an exhaust-air semi-transverse system. It should be noted that reversing the direction of the fans can impact the efficiency of the system.

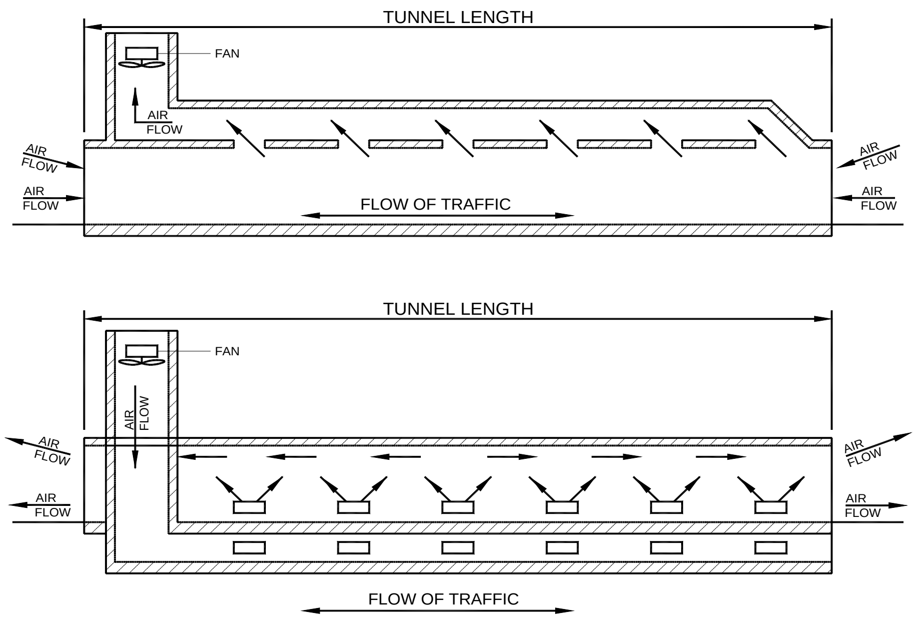


Figure 1.14 – Semi-transverse ventilation.

Full-Transverse Ventilation - Full-transverse ventilation systems use two air ducts, one for supply air and one is for exhaust air. With a fully transverse system, the tunnel bore is not used as part of the ductwork. This method is used primarily for longer tunnels with heavy traffic. A pressure difference is created between the supply and exhaust ducts to control the air flow. The ducts are commonly located in the ceiling (Exhaust Air) and invert (Fresh Air) but may also be located along the sides of the tunnel. Figure 1.15 shows an example of a fully transverse ventilation system.

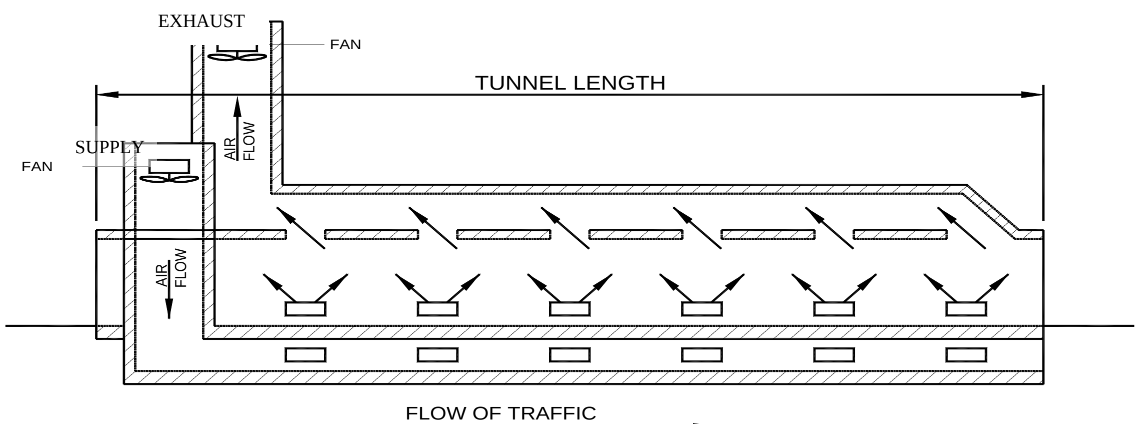


Figure 1.15 – Full-transverse ventilation.

Single-Point Extraction – In conjunction with semi- and full-transverse ventilation systems, single-point extraction can be used to increase the airflow during a fire event. The system works by allowing the opening size of the exhaust flues to increase during the emergency. This can be accomplished by remotely controlled louvers.

1.4.9.2 **Equipment**

Ventilation equipment encompasses fans, motors, drives, attenuators, and dampers. The fans are the primary component of the system.

(a) Axial and Centrifugal Fan Types

Axial fans and centrifugal fans are common (See Figure 1.16). Axial fans discharge air parallel to the axis of the impeller rotation whereas centrifugal fans discharge air at 90 degrees to the axis of rotation. Axial fans are common for longitudinal ventilation systems; centrifugal fans are used with semi and full transverse ventilation systems as well as Saccardo nozzle type systems with longitudinal ventilation.

(i) Axial

There are two main types of axial fans—tube axial fans and vane axial fans. Both types move the air parallel to the impeller shaft or along the longitudinal axis of the fan. The difference between the two is the addition of guide vanes on one or both sides of the fan impellor. These additional vanes allow the fan to deliver pressures that are than a typical tube axial fan. The most common application of an axial fan is to mount them horizontally on the tunnel ceiling of the tunnel at various intervals.

(ii) Centrifugal

Air enters centrifugal fans parallel to the blade shaft and discharges perpendicular to the axis of rotation. For tunnel applications, centrifugal fans can be either backward-curved or airfoil-bladed. Centrifugal fans are predominantly located within ventilation or portal buildings where they are connected to supply or exhaust ductwork. These fans are commonly selected over axial fans for these applications due to their high efficiency and cost effectiveness.

Tube Axial Fan | Vane Axial Fan | Centrifugal Fan

Figure 1.16 –Various types of ventilation fans.

(b) Supplemental Equipment

(i) Motors

Electric motors are commonly used to drive the fans. Motors can be constant speed or variable speed, depending on the design requirements. According to the National Electric Manufacturers Association (NEMA), motors should be able to withstand a voltage and frequency adjustment of +/- 10 percent.

(ii) Fan Drives

A motor can be connected to the fan either directly or indirectly. Direct drive fans have motors that are connected to the impellor shaft directly. Indirect drives allow for more flexibility in the location of the motor; and the motor is connected to the impellor shaft using belts, chains, or gears.

(iii) Sound Attenuators

Some tunnel exhaust systems are located in regions where noise levels must be controlled, such as near residential settings. Noise can be mitigated by installing noise attenuators either mounted directly to the fan or within ductwork along the system.

(iv) Dampers

Dampers are devices that help control the flow of air within the ductwork. They are usually positioned fully open or fully closed, but some can be operated in an intermediate position.

1.4.10 **Lighting Systems**

There are various lighting systems used in tunnels. These include fluorescent, high-pressure sodium, low-pressure sodium, metal halide, and LED lighting. The systems are chosen based on their life-cycle costs and the amount of light provided. Highly reflective surfaces on the walls and ceiling, such as tile or metal panels, are used to minimize the amount of light required for proper luminescence (See Figure 1.17).

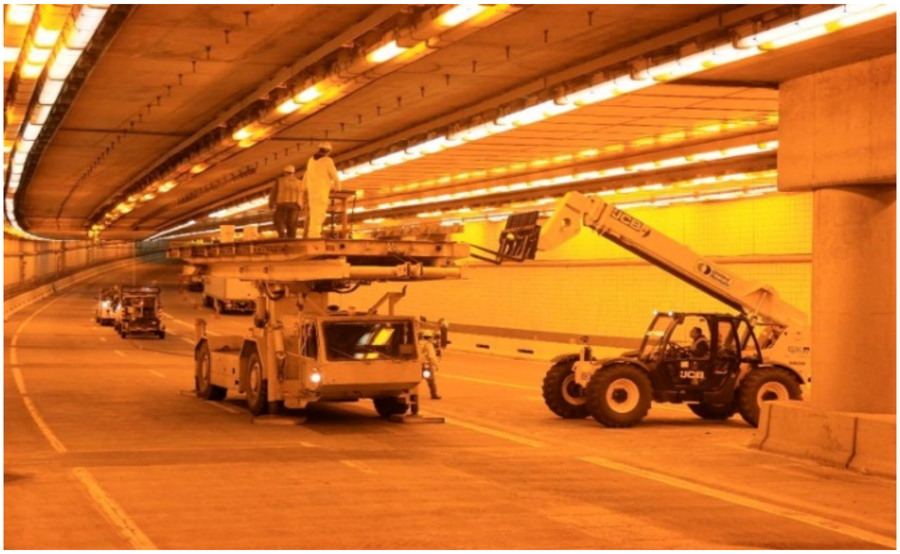


Figure 1.17 –Tunnel lighting systems.

In the past, fluorescent lights were the most common type used to line the entire roadway tunnel; and other types of lighting were provided at the portals to increase the illumination levels for the transition to daylight driving conditions. High-pressure sodium lamps, low-pressure sodium, and metal halide lamps have also been used with success. Currently, lighting technology has been moving towards LED lighting because of the greater efficiency and lower requirements for power consumption.

1.4.11 **Fire and Life Safety Systems**

These systems consist of control panels, initiating devices (e.g., heat and smoke detectors, pull-stations, cameras), notification appliances (e.g., strobes, horns, radios, and variable message signs), wiring, conduit, and cables, and emergency egress signs, fire hydrants and extinguishers. The fire and life safety systems system are used to detect a fire during an emergency, to initiate an emergency response, and to inform tunnel users of appropriate emergency actions to take (See Figure 1.18).

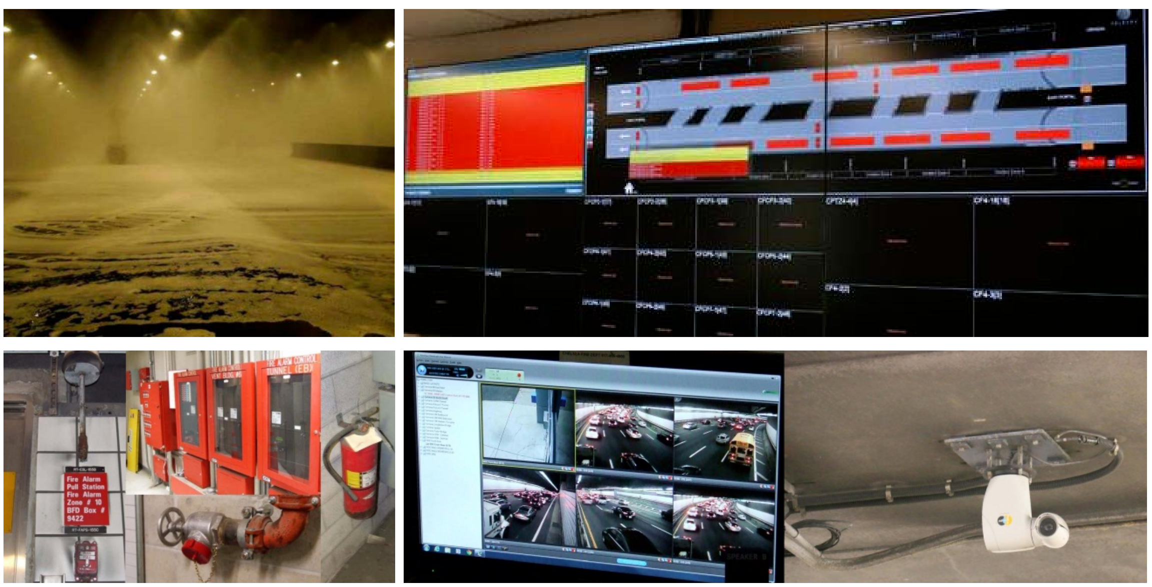


Figure 1.18 – Components of fire and life safety systems that are used in highway tunnels.

1.4.12 **Other Systems**

Other common tunnel systems include power distribution systems, traffic management systems, communications, and security systems.

1.4.12.1 **Power Distribution Systems**

Power distribution systems include the electrical equipment, wiring, conduit, and cable used for distributing electrical energy from the utility supply (i.e., service entrance) to the line terminals of equipment. The equipment includes transformers, switchgear, switchboards, panel boards, motor control centers, starters, switches, and receptacles.

1.4.12.2 Signs and Messaging Systems

Tunnel traffic control devices can be mounted on the tunnel walls, the overhead ceiling or on the barriers at the portals. These devices include reflective signs and illuminated displays that use light bulbs or LEDs to convey messages. These devices can provide directions and warnings to motorists and evacuating pedestrians in the event of a fire or other hazard.

1.4.12.3 Communications

The communication system consists of all devices that allow communication to take place inside the tunnel. Examples of these systems include emergency phones that are located at intervals along the length of the tunnel bore and radios by which central operations and/or maintenance crews communicate. The components generally include supervisory control and data acquisition systems (SCADA), closed-circuit television (CCTV), cameras, loudspeakers, phones and radios, as well as the cables, wires, or other equipment that is needed to operate the systems.

1.4.12.4 Security Systems

Security systems include surveillance systems, communication systems, stopped traffic detection system, wrong way detection systems, CCTV, SCADA systems, chemical/biological/radiological monitoring systems, detection systems for explosions, traffic management systems, and systems that control access to the tunnel, equipment rooms, or command and control centers. Locking mechanisms on doors and other entry and exit points may be included as part of the tunnel security system.

1.5 TOMIE Manual Overview

The TOMIE Manual serves as a resource for tunnel operations, maintenance, inspection and evaluation. Chapter 1 contains background information regarding the development of the NTIS. This chapter also reviews the fundamentals concepts of highway tunnels such as tunnel construction methods and shapes, liner types and finishes, slabs and wearing surfaces, and tunnel systems like drainage, ventilation, lighting, power and communication.

1.5.1 Operations

Chapter 2 discusses the operation of tunnels. This chapter presents an organizational structure for the operating staff at the tunnel facility; and it discusses the generalized duties for these staff positions. Normal operating procedures, incident management, and operations protocols are also discussed.

1.5.2 Maintenance

Chapter 3 discusses the maintenance of tunnels to include preventative, on-demand, and rehabilitation. The chapter provides maintenance guidelines for structural, civil, and functional systems and tunnel elements.

1.5.3 Inspection

Chapter 4 discusses the development of an inspection program to include a brief overview of the NTIS. The responsibilities of the tunnel inspection organization, qualifications of inspection personnel, inspection procedures and practices, and the various types of tunnel inspections are summarized. Information is provided on developing the health and safety plans, inspection equipment, typical tunnel defects, owner defined elements, and critical findings.

1.5.4 Evaluation

Chapter 5 focuses on the evaluation of tunnel systems. The main topics include personnel qualifications, supplemental inspection and testing, methods for evaluating various tunnel system components such as risk based assessments, priority classification, and basic cost estimating. Tunnel management is also discussed. The regulatory requirements for the load rating of highway tunnels are explained.

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TOMIE MANUAL

CHAPTER 2

OPERATIONS

Chapter 2 – Tunnel Operations

2 Introduction

The operating requirements vary among tunnel facilities because of the traffic level, the feasibility of alternative routes, accessibility to existing utilities, availability of emergency responders, and other conditions specific to each tunnel. Functional systems within the tunnel must be integrated with operational procedures to include the mechanical equipment, electrical components, lighting fixtures, fire and life safety systems, signs and security equipment installed within the tunnel.

2.1 Scope of Chapter 2

Included in Chapter 2 are the essential roles and responsibilities of the tunnel staff, normal operating procedures, and emergency response guidelines for vehicle collisions, fires, explosions, floods and earthquakes.

2.2 Tunnel Facility Personnel

Highway tunnel agencies need to employ the appropriate personnel to operate the tunnel safely and provide reliable levels of service. Since tunnel operations differ among various facilities, the duties and responsibilities need to be organized to match requirements for each tunnel facility. An example of a tunnel organization with brief position duties is included below:

- **Tunnel manager** – This person manages the tunnel facility and is responsible for establishing an effective operating program that includes complying with applicable laws, regulations, and policies; managing budgets, payments, funding, and financing; maintaining tunnel facility records; approving contracts and major purchases; and hiring, organizing, and training personnel.

- **Facility engineer** – This individual leads the technical program for the tunnel facility and is responsible for establishing effective tunnel maintenance programs and leading capital improvement projects. This person performs basic engineering duties such as evaluating structural defects, safety concerns, and maintenance records; developing quality programs, performing life cycle analyses, prioritizing major repairs, recommending upgrades and replacements; specifying the performance requirements for tunnel systems; and negotiating contracts with contractors, consultants, and vendors.

- **Tunnel supervisor** – This individual is in-charge of the overall day-to-day operation and maintenance activities This person generates work assignments, issues work orders, schedules repairs and maintenance, orders spare parts and equipment, manages traffic and lane closures, responds to incidents, conducts quality reviews, approves the work of contractors and consultants, and communicates problems to the tunnel manager and facility engineer.

- **Tunnel operators** – These individuals manage tunnel operations by monitoring traffic, congestion, accidents, over-height vehicles, variable message displays and output from control signals. They monitor air contamination and ventilation, fan performance, electrical supply and power consumption, lighting intensity, weather conditions, water accumulation and pump operation. They are responsible for activating emergency systems and coordinating emergency response for serious incidents.

- **Tunnel forepersons –** Forepersons lead a small team of discipline-specific specialists and/or general laborers. The foreperson is the senior technical specialist for the group and serves as a resource to the tunnel facility in a specialized area of practice. This person is qualified through a combination of formalized education, on-the-job training, and relevant experience. The foreperson is responsible for such tasks as coordinating the duties of subordinate staff in their group, enforcing quality programs, checking the work performed, closing-out work orders, inventorying spare parts, and generating supply reorder lists.

- **Tunnel mechanical specialists –** The mechanical specialist performs tasks that are related to mechanical technology. Typically, this person has completed a certified program of formalized education and on-the-job training in mechanical technology. The specialist performs routine maintenance such as oil changes, filter changes, cleaning of blades, replacing belts, etc. This specialist works with different types of mechanical equipment to include ventilation fans, pumps, ducting, and air conditioning units. The mechanical specialist should also be able to diagnose routine mechanical problems and fully implement the designated quality measures during mechanical repairs.

- **Tunnel electrical specialists –** The electrical specialist performs tasks that are related to electrical technology. Typically, this person has completed a certified program of formalized education and on-the-job training in electrical technology. The specialist works on electrical control, power distribution, and electronic drive systems and performs functions such as changing batteries, operating motors, running generators, replacing or repairing lighting fixtures and ballasts, and checking various fire detection and suppression equipment, carbon monoxide detectors, and CCTV cameras. The electrical specialist should also be able to diagnose routine electrical problems and fully implement the designated quality measures during electrical repairs.

- **Tunnel electronics specialists** - The electronics specialist performs tasks that are related to electronics technology. Typically, this person has completed a certified program of formalized education and on-the-job training in electronics. The specialist works with low voltage power and communication equipment and support equipment and systems such as power switchgears and panel boards with amp meters, power meters and frequency meters, environmental control systems, programmable logic controllers (PLCs) and monitoring systems, fire alarm systems, HVAC control systems, lane control signals, variable message boards, and CCTV systems. The electronics specialist should also be able to diagnose routine problems and fully implement the designated quality measures during repairs.

- **Tunnel laborers –** Laborers serve as versatile workers that perform many tasks such as cleaning drains, washing structures, cutting grass, painting, unloading supplies, stocking parts, general housekeeping, and installing light bulbs. Laborers also support discipline-specific specialists (i.e., mechanical, electrical, electronic) by moving heavy objects, cleaning equipment, tightening bolts, etc. Laborers facilitate tunnel operations by directing traffic, placing barricades, clearing debris, shoveling snow, removing disabled vehicles, etc.

- **Safety officers –** The safety officers coordinate the emergency response with local fire departments, medical transport units, and police. These officers may have experience as emergency dispatchers, firefighters, or paramedics. Safety officers participate in disaster recovery planning and the development of response strategies for various tunnel specific hazards. Safety officers generally have some level of firefighting and rescue equipment on site that is appropriate for the tunnel facility. The safety officers conduct drills and training for emergency preparedness. These officers also serve as liaisons between the tunnel facility and emergency response to include firefighters, ambulance services, and medevac units.

- **Security officers –** The security officers respond to emergency situations, support emergency operations, patrol the facility, implement weather advisories, escort hazardous vehicles, inspect cargo, etc. Security officers participate in the development of response strategies for various tunnel specific threat scenarios. These officers may have experience in police or tactical units. They should receive specialized training in tunnel security. Security officers set up patrol vehicles and towing equipment on site and serve as liaisons between various police units and the tunnel facility.

2.3 Normal Tunnel Operations

Normal tunnel operations consist of routine tasks that ensure the safe and efficient flow of traffic through the tunnel facility. These tasks typically include:

- Monitoring traffic flows 24/7 using surveillance equipment and incident detection systems.
- Studying weather conditions and forecasts.
- Clearing roadway hazards (e.g., debris, ice, snow, and incidents)
- Inspecting critical areas to confirm that safe conditions exist (e.g., overhead equipment, roadway surfaces).
- Checking functional systems (e.g., ventilation, air quality monitors, pumping, lighting, CCTV).
- Servicing equipment and periodic exercising of all movable components (e.g., fans, pumps, emergency generators).
- Cleaning of tunnel facility, portal buildings, ancillary structures, and grounds.
- Maintaining vehicles and equipment.
- Completing daily logs and checklists.
- Processing work orders (e.g., initiating, scheduling, completing, closing).
- Checking information (e.g., lane signals, signs, and variable message boards).
- Evaluating sensors and meters (e.g., carbon monoxide, oxygen, explosive gases, and luminance).

2.3.1 **Maintaining Traffic Flows**

Traffic flows through the tunnel in a defined direction of travel. Unidirectional traffic refers to one-way traffic within a tunnel bore. Bidirectional refers to two-way traffic within a tunnel bore. Contra-flow refers to the temporary condition of changing from unidirectional traffic within a bore to bidirectional flow or the reversing of travel within the bore.

2.3.2 **Tunnel Traffic Closures**

Tunnels must sometimes be closed to traffic to conduct maintenance, repairs, rehabilitation projects, and inspections. Depending on the circumstances, a tunnel may be partially closed to traffic by shutting down a lane, or it may be fully closed by shutting down the entire bore. Typically, tunnel closures are made during off peak hours when practical for routine maintenance or inspections.

When closures for major repairs or rehabilitation are scheduled, public notification should be provided well in advance. The public may be informed a number of way such as using media announcements, web announcements, and variable message signs on roadways. Communication with police, emergency personnel, and utility companies is essential so all parties involved are prepared for incident management.

Traffic control devices are used in accordance with the latest version of *The Manual on Uniform Traffic Control Devices* published by the Federal Highway Administration.

http://mutcd.fhwa.dot.gov

2.3.2.1 **Temporary Lane Closures**

Lane closure procedures are influenced by the type of traffic flow in the tunnel and the number of traffic lanes. Lane closures involve:

- Regulated flow is a term used when alternating traffic flows must be managed by the tunnel operator. If this is a temporary condition of short duration, then traffic control can be managed by tunnel facility personnel or police officers. If it is a long-term closing, traffic lights are a good option.
- Restricted flow is a term used when a lane is shut down in a uni-directional tunnel with two or more traffic lanes.

2.3.2.2 **Temporary Bore Closures**

Full bore closures involve rerouting traffic to another bore or establishing a detour with an alternate route. If work is of a short duration, the operating personnel may simply stop traffic while the work is being completed such as when tunnel washing can be accomplished in a short period of time during off-peak hours.

Rerouting Traffic to Another Bore – When there are two or more adjacent bores, traffic can be rerouted through the other open bores, which might create bi-directional traffic. An assessment of the traffic control devices and emergency egress signs will be necessary.

Detours – When a suitable alternate route is available, the traffic can be detoured. The rerouting of traffic requires an assessment of the impacts to the neighborhoods and communities along the detour. Neighborhoods often bear significant social, economic, and environmental costs associated with traffic due to gridlock, noise, lights, fumes, repair work, and congestion; and the rerouting of hazardous materials through vulnerable communities are a concern.

2.4 Emergency Response and Incident Management

Incidents requiring immediate action can occur in tunnels. Emergency originate from fires, fuel spills, hazardous material releases, earthquakes, floods, rock slides, landslides, severe weather, and criminal acts. A thorough inspection of the tunnel damage should be conducted in accordance with the damage inspection procedures identified in Chapter 4 of the TOMIE Manual. These events often require partial or complete tunnel closure followed by the rerouting of traffic while the tunnel is repaired.

Procedures need to be established so that emergencies can be dealt with in a timely manner. Certain incidents may require immediate contact with emergency responders (e.g., fire, police, and utility companies). Other events may not be as severe and can be handled by tunnel facility personnel. Drills should be conducted periodically for conditions such as electrical blackouts, vehicle accidents, over height vehicle strikes, hazardous cargo releases, emergency evacuation, and other threat scenarios deemed appropriate for the tunnel facility.

2.4.1 **Impacts and Collisions**

Impact damage frequently occurs in tunnels from over-height vehicles near the portals. After an impact incident, traffic should be stopped at the tunnel entrance until the situation can be sufficiently assessed. If there are any injuries, emergency personnel should be immediately notified. Once the conditions are rendered safe by removing abandoned vehicles, removing damaged vehicles, clearing debris, repairing pavement, and inspecting for damage to the tunnel, the tunnel can be restored to service (See Figure 2.1).

Figure 2.1 – Collisions within tunnels.

2.4.2 **Fires**

Fire incidents often require emergency ventilation measures to exhaust the smoke, control superheated gasses, and provide tenable escape routes (See Figure 2.2). There are a number of ventilation concerns during a fire such as back-layering of smoke, fueling oxygen to the fire, exhausting superheated gasses, pressurizing escape routes to repel smoke and superheated gasses. In order to minimize potential ventilation errors during a fire event, written guidelines should be established for the operation of the mechanical ventilation system for various scenarios.

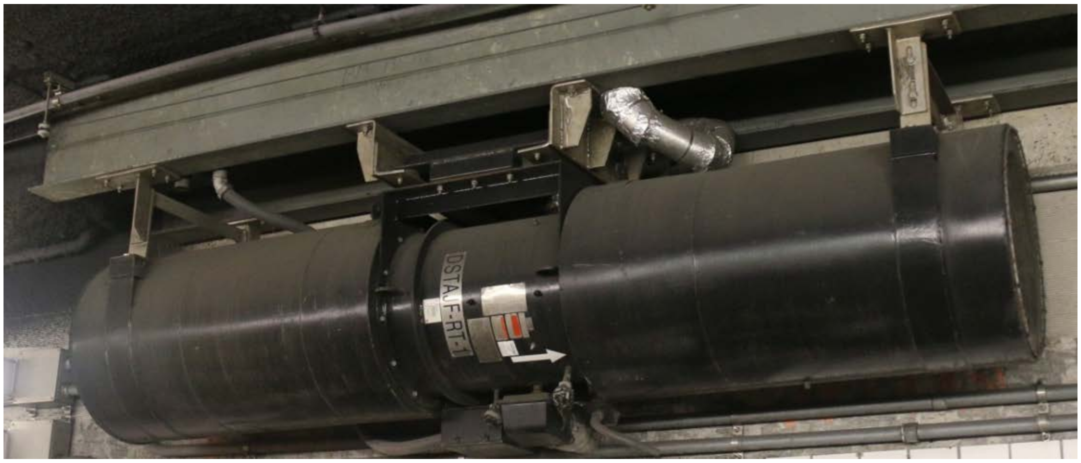

Figure 2.2 – Emergency ventilation fan.

Tunnel fires can be very difficult to extinguish; and these fires can produce large amounts of toxic smoke and dangerous heat that can fill the tunnel (See Figure 2.3). The tunnel operator has a responsibility to protect the tunnel occupants. Rapid detection is essential in this safety chain, and surveillance equipment, fire and smoke detectors, and Supervisory Control and Data Acquisition SCADA systems play a major role in the rapid detection of fires (See Figure 2.4). Modern tunnel facilities are protected by fire extinguishers, sprinkler systems, and deluge systems (See Figure 2.5).

Figure 2.3 – Tunnel fires can be extremely dangerous.

Figure 2.4 – Incident detection systems facilitate a rapid response to the emergency.

Figure 2.5 – Fire protection equipment and accessible escape routes.

Fire support personnel and other first responders should be notified immediately; however, emergency responders may not always arrive at the scene in time to assist with the evacuation. In the period before the emergency responders arrive on the scene, self-rescue should be encouraged. The vehicles in front of the accident site should be directed to exit out of the tunnel in the direction of travel. The tunnel occupants trapped behind the fire and debris generally must evacuate on foot.

Intuitive wall signage, audible messages, and lights that direct escapees to designated cross passages, portals, escape routes, and areas of refuge help increase survivability. Signs that display the direction and distance to the nearest emergency exit have been shown to be most effective. Information is available from the Permanent International Association or Road Congress (PIARC) and American Association of State Highway and Transportation Officials (AASHTO), which are conducting studies on the influence of user behavior on sign effectiveness under simulated emergency conditions.

Tunnel personnel should respond in accordance with established protocols, training, and drills. Traffic should be stopped in all adjacent bores since the crossovers might be used for evacuation and emergency response purposes. Fuels and other combustibles can drastically increase the severity of a fire. Spilled fuel may also flow to collection points in the drainage system or be transported to other parts of the tunnel. Some drainage systems may discharge to locations outside of the tunnel. Monitors should be evaluated to gauge the explosive gas levels after a crash at various collection points in the drainage system.

2.4.3 **Floods**

Flooding occurs due to water entering at the portals from heavy rainfall, overflowing rivers, rising water levels and increased wave heights, dam or levee breaches, and water main ruptures. To prevent flooding from water and sewer supply lines, the utilities near the tunnel should be inspected periodically. Most tunnels have pump systems that help prevent flooding, but flooding may still occur when the water rapidly enters the tunnel. Some tunnels also have flood gates installed at their portals to seal out flood water from extreme weather events (See Figure 2.6). If flooding is anticipated, the tunnel should be closed ahead of time to prevent endangering any motorists using the tunnel.

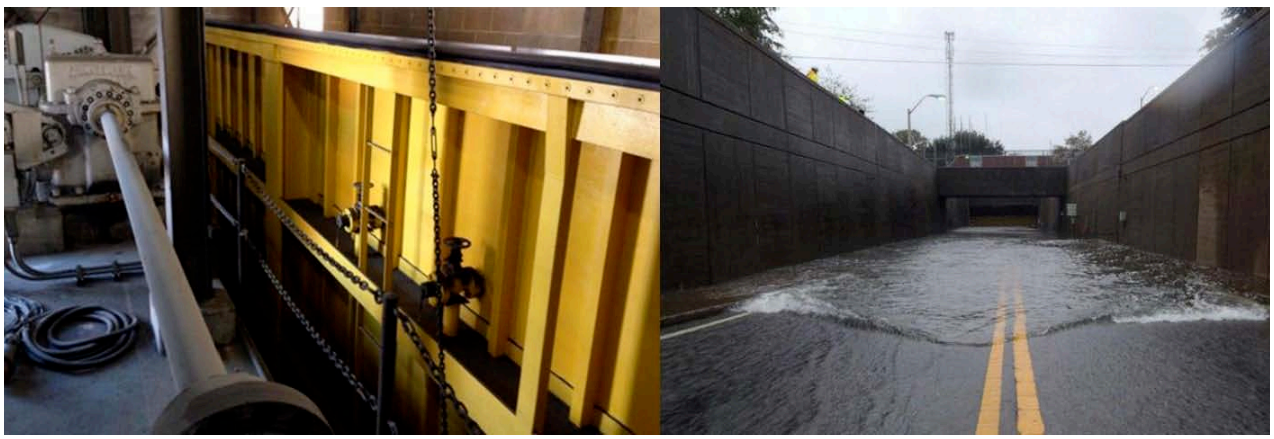

Figure 2.6 – Tunnel flood gates (left) and photograph of a flooding event taking place (right).

Tunnel facility personnel should be prepared to respond quickly to a potential flood event, which will help to minimize the damage to the tunnel equipment and systems. After a flood event, the embankments and slopes around the tunnel should be checked because they may become unstable due saturation with water. The functional systems must be checked to ensure that they are working as intended. Electrical systems can be ruined by floodwaters, especially if they are exposed to saltwater in the process. The potential for electric shock also needs to be evaluated prior to reentering the tunnel.

2.4.4 **Earthquakes**

Seismic events occur without warning; and vehicles may be present in the tunnel when the earthquake strikes. Depending upon the magnitude of the seismic event and the design of the tunnel to withstand certain seismic forces, motorist may be at risk and the tunnel might be severely damaged (See Figure.2.7). This damage could range from movements at joints and cracks to detachment of materials to severe damage to equipment and supports. Large quantities of water may also penetrate through tunnel cracks and joints that widen during the shaking of the ground.

Figure 2.7 – Earthquake damage to tunnels.

Depending upon the event, the tunnel may need to be closed until earthquake aftershocks have diminished. It is also advised to be aware of tsunamis in low lying areas after a seismic event. As with other emergency events, service should be restored safely and as quickly as possible, following a thorough safety inspection.

2.4.5 **Security Events**

Tunnels are complex infrastructure with unique challenges from a security perspective (See Figure 2.8). Tunnels contain a number of vulnerabilities unique to the particular tunnel as well as those common to most tunnels. Security risks to highway tunnels range from threats of terrorism to minor criminal vandalism. Tunnels also house utilities and communication lines. With some exceptions, mitigating highway tunnel security risk involves many of the same measures described for fire, flood, and impact from other incidents. Explosions generate many of the same deleterious effects as fire and impact; however, the shockwave caused by an explosion can potentially do much more extensive damage to the tunnel structure. Explosions can be accidental or they can be deliberate acts. Accidents can be caused by increased use of alternative fuels in private and commercial vehicles, spilled fuel accumulated in drainage sumps, and explosive gasses leached from certain rock formations with inadequate ventilation.

Figure 2.8 – Police escort through tunnel to mitigate safety concerns.

Quantitative methods can be used to evaluate security risk to tunnels that include threats, vulnerabilities, and consequences. One method developed for the Transportation Security Administration by the US Army Corps of Engineers (**See Appendix A**) evaluates risk in two distinct areas: Operational Risk and Casualty Risk. This is a component-level methodology that evaluates mitigated and unmitigated threats. The tunnel owner can evaluate the effectiveness of strategies to minimize damage, limit loss of life and function, and allocate resources. The Operational risk analysis allows an owner to select an “Operational Loss of Service” damage level and then evaluate the current and mitigated threat sizes relative to the specified damage level. The Casualties Risk Analysis uses a scenario-based procedure to select a threat size and location. From this information, the current and mitigated casualties are evaluated. This risk process is used for new and existing designs to develop mitigation strategies and to effectively reduce costs. By using the quantitative risk assessment, the multi-hazard concept of operations can be developed.

Threats considered in this model include explosives (e.g., vehicle borne and hand-emplaced), fire, cutting devices, impact, and chemical spills. Each threat should be evaluated based on location and its impact on vulnerable components. By understanding the vulnerabilities and using risk based assessment, tunnel security can be enhanced. The process for tunnel vulnerability assessment should be a methodical and a logical basis for action that incorporates expert analysis, organized risk calculation processes, evaluation of baseline tunnel vulnerabilities and risk using qualitative and quantitative analysis, and re-evaluation of risk to determine mitigation effectiveness.

The National Cooperative Research Program and the National Cooperative Highway Research Program (2006) jointly produced a report on making transportation tunnels safe and secure to include discussions on possible hazards and threats, case studies, tunnel elements and vulnerabilities, countermeasures, and system integration. It also provides recommendations for future research.

2.5 Preparation of Plans and Procedures

The operation of each highway tunnel is a function of the age of the facility, the ventilation, electrical, and lighting equipment; location and geometry of the tunnel; availability of emergency support; and the sophistication of equipment, tunnel systems and operation center. Each tunnel facility should develop site-specific operation protocols and staffing requirements for both normal and emergency operating conditions.

2.5.1 **Emergency Response Plan (Site Specific)**

Emergency response plans and mitigation strategies should be developed based on the "buy-in" of multiple stakeholders including the tunnel management and operation team, firefighters, police, other emergency responders, security professionals, and owners of co-located assets. Each tunnel should have an emergency response plan tailored to meet the demands of the appropriate threat scenarios. The following are examples of actions in a site-specific emergency response plan:

- Assess the location and severity of the emergency.
- Close the tunnel roadway to nonessential vehicles; Note that emergency vehicles may still need access into the tunnel.
- Close adjacent tunnel since evacuees might need to escape through crossover passageways and use the adjacent tunnel. Evaluate whether emergency vehicles need to use the adjacent tunnel to carry out the emergency response.
- Adjust ventilation output as necessary for fire and smoke control.
- Notify first responders: Fire, police, emergency medical personnel, management, and others.
- Prior to first responders arriving at the site, the motorist should be encouraged to perform self-rescue as conditions permit.
- Initialize warnings on variable message boards and other communication devices.
- Assist in safely clearing vehicles from the tunnel.
- Perform an inspection after the event is resolved and the conditions are safe to do so.
- Clear the tunnel of debris.

2.5.2 **Training and Drills**

An effective emergency response ensures that all responsible personnel receive training and participate in drills with firefighters and other first responders. The frequency and nature of the training and drills should be described in each tunnel's concept of operations. Since all tunnels have features that require unique protocols, the concept of operations should be tailored for each tunnel. Among the items to be considered are: ventilation control for various scenarios, traffic management (e.g., how to close the tunnel quickly), impact on adjacent bores, communication among first responders and between the tunnel operation center, communication with tunnel users, and how to safely and quickly evacuate users who are at risk. Training should be provided for new tunnel personnel and periodically thereafter, i.e. refresher training for experienced workers.

2.5.3 **Pedestrian Evacuation Route Signage**

Some countries have enhanced the exit doors of tunnel by incorporating flashing LED lights and audible messages to help evacuees locate the exit or safe room when smoke engulfs the tunnel. A scan of European tunnels reported widespread use in Europe of clear and consistent signs for emergency escape. The findings and details are in an FHWA report from June 2006: *Underground Transportation Systems in Europe: Safety, Operations and Emergency Response*.

(http://international.fhwa.dot.gov/uts/)

A current study is underway at the National Cooperative Highway Research Program to evaluate signs, markings and auditory messages in order to develop guidelines for use in the United States. An example of the type of sign that is under consideration is shown in Figure 2.9.

Figure 2.9 – Proposed sign for emergency escape route.

2.6 Summary

It is paramount that the operation of a highway tunnel be based on the safety of the traveling public. The tunnel should also provide reliable levels of service. Since tunnels are resource intensive, they should be operated by competent staff with well-defined areas of responsibility. The operating procedures should be appropriate for all of the requirements of the tunnel facility. The emergency response for the tunnel facility should address various appropriate scenarios taking into full account the ramifications of possible tunnel closure. It is important that health and safety plans be developed for the tunnel.

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TOMIE MANUAL

CHAPTER 3

MAINTENANCE

Chapter 3 – Maintenance

3 Introduction

An effective maintenance program helps reduce costs, decrease the number of tunnel closures, increase public safety, and ensure adequate levels of service. To maximize efficient use of resources and minimize costs, maintenance programs should be optimized. When large-scale repairs and upgrades are implemented, these projects are typically referred to as tunnel rehabilitation. 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

3.1 Scope of Chapter 3

The fundamental causes of deterioration and corrosion in tunnels are reviewed in this chapter, and various preventative and on-demand maintenance strategies are presented. This chapter also introduces methods aimed at controlling groundwater seepage. Various repair techniques and rehabilitation schemes are presented with links provided to suggested maintenance tables.

3.2 Deterioration and Corrosion

Groundwater induces moisture into the tunnel which can accelerate the rate of deterioration and corrosion (See Figures 3.1 and 3.2) especially if road salts, dissimilar metals, and stray currents are involved. Some of the common degradation processes associated with groundwater include:

- Corrosion, section loss, and reduced element strength.
- Removal of material particles and cements, especially when the groundwater is acidic.
- Concrete spalling due to corrosion of reinforcing steel.
- Failure of electrical and electronic components due to corrosion and short circuiting.
- Freeze thaw damage in colder climate.
- Deterioration of the protective finishes and coatings.
- Removal of soil particles with voids created around the tunnel liner.
- Redeposit and clogging of drainage systems.

Figure 3.1 – Groundwater induced corrosion and deterioration.

Figure 3.2 – Leakage through shotcrete liner (NCHRP, 2010).

3.3 Developing an Effective Tunnel Maintenance Program

Ideally, the maintenance strategies of a tunnel facility should strike a balance between preventative maintenance and on-demand maintenance. Safety, service requirements, and costs must be considered. When approximately 70% to 80% of all maintenance activities are performed under a preventative maintenance approach, it is considered to be good practice.

The maintenance program should be developed from the existing records of a tunnel facility. Written procedures should be followed to ensure that the tunnel facility receives sufficient maintenance. *If safety or structural concerns are identified in the process of carrying out maintenance tasks, then the defects should be addressed*.

3.3.1 **Preventive Maintenance**

Preventive maintenance is conducted to reduce likelihood of failure and to extend the service life of components. An optimized maintenance approach focuses on various preventative maintenance schemes such as cyclical, conditional, and predictive-based methods. With cyclical methods, the maintenance is performed at pre-determined intervals. This approach is common when there is an established service-life. Conditional maintenance draws upon observations and measurements to gauge the onset of failure. An example of this scheme is the use of wear indicators on fan belts, drive chains, and sprockets. Predictive maintenance is based on mathematical forecasting models and statistical analysis. These methods use data-driven, risk-based strategies as discussed in Chapter 5 of this manual.

3.3.2 **Corrective or On-Demand Maintenance**

On-demand maintenance is sometimes referred to as corrective maintenance. This type of maintenance is the most effective strategy against difficult-to-predict occurrences such as damage from vehicle impacts, sudden equipment malfunctions, or unanticipated tunnel system failure. Contingency plans should be developed in advance to facilitate the repair process and return the tunnel to service.

3.3.3 **Tunnel System Rehabilitation**

Individual tunnel systems are often rehabilitated when they are near the end of their useful life. Rehabilitation, also called refurbishment, implies that a large-scale repair programs is being developed with extended durations, substantial engineering input, and substantial costs. Tunnel rehabilitation includes projects such as overhauling the ventilation systems, upgrading the fire suppression equipment, replacing the lighting system, or making extensive structural repairs.

3.4 Types of Maintenance Activities

Maintenance activities include removing debris, snow, and ice; washing tunnel structures, flushing drains, tightening bolts, and changing light bulbs; and servicing equipment, painting fixtures, and restoring pavement. Maintenance also involves conducting tests, verifications, measurements, and calibrations on equipment, machines, and systems.

3.4.1 **Removing Debris, Snow and Ice**

Debris, snow, and ice present a number of safety concerns. Debris should be removed from the tunnel on a regular basis since it could obstruct vision, damage vehicles, foul equipment, or present a fire or safety hazard. In cold regions, icicles above the roadway should be removed since they could damage vehicles. Deicing agents should be used to clear ice from sidewalks, roadways, and approaches. Ice should also be removed from areas that are not designed to carry potentially ice loads (See Figure 3.3).

Figure 3.3 – Ice formation in plenum area above ceiling slab.

3.4.2 **Tunnel Washing**

The tunnel should be washed when the interior becomes dull with dirt (See Figure 3.4). Washing is also recommended to make the inspection work easier. The washing process consists of spraying the tunnel with water and detergents, scrubbing the surfaces with rotating brushes, and rinsing off the soap and grime using water jets. The frequency of washing varies from one tunnel facilities to the next because of environmental conditions, traffic levels, and the type of vehicles such as diesel burning trucks. Some tunnels should be washed quarterly, while others might only be cleaned annually. Tunnel washing is sometimes suspended during winter months to prevent the formation of excessive ice buildup.

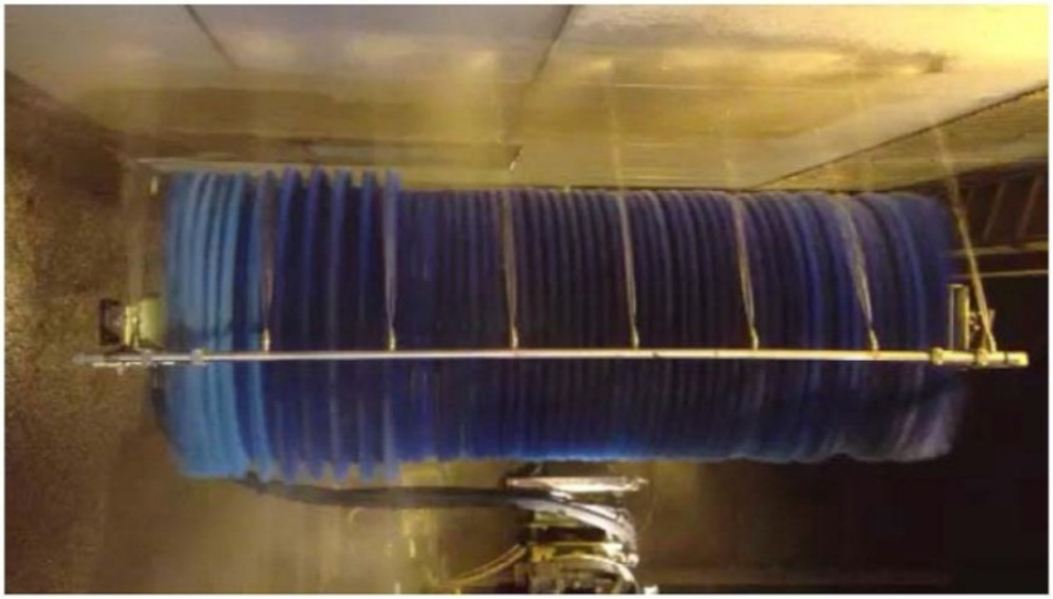

Figure 3.4 – Washing the tunnel.

3.4.3 Servicing Vehicles and Equipment

Vehicles and equipment should be serviced periodically to ensure readiness and performance. When servicing vehicles, the engines and motors should be checked for things such as appropriate fluid levels, unusual sounds, excessive temperatures, and abnormal vibrations. The gauges and readout units should indicate normal operating levels. Any leaks from oil, grease, fuel or fluid should be noted in the log book and remediated. When checking the electrical components, look for torn, ripped, or frayed insulation and signs of corrosion, arcing, or overheating. Preventative measures include actions such as:

- Routinely monitor equipment, collect data, record findings, and maintain logs.
- Analyze the data to identify if there are any trends (vibration, oil analysis, operating temperatures, bus temperatures, lighting levels, water pressure) that indicate component failure.
- Stock a reasonable supply of spare parts.
- Sometimes equipment can be operated at reduced capacities but only when it is safe to do so.
- Negotiate prices in advance with specialty contactors and equipment vendors.
- Evaluate rental equipment options and negotiate rental agreements in advance of the equipment breakdown.
- Retain manufacturer documentation (e.g., operation manuals, spare parts lists, recommended maintenance practices, schematics).
- Document repair processes and replacement activities. Identify the key issues and develop aids such as checklists and schematics.
- Maintain cost records for parts, equipment, contracts, and labor.
- Provide mentoring and develop a training program for all of the maintenance staff.

3.4.4 Drainage Inlets and Pipes

Roadway drain inlets should be cleaned of debris and flushed with water to prevent clogging. These activities should be scheduled with tunnel washing activities. Plumbing snakes and down-the-hole video cameras can be inserted into pipes with cleanouts to help identify problems areas within the concealed string. The drainage system should be monitored during periods of cold weather to reduce any occurrence of pipe freezing and possible subsequent bursting.

3.4.5 Luminaire Cleaning and Replacement

Lighting and visibility play an important role in accident prevention. Lights should be easy to service to limit lane closures and maintenance time. Lights should be sealed from harmful environmental effects and keep out moisture, bugs, and dust. Luminaires that facilitate rapid bulb replacement are ideal.

3.4.6 Pavement Markings and Signs

Pavement markings and signs should be cleaned when they become dull and painted, as necessary, for luminosity. When traveling through the tunnel at the allowable speeds, the motorists should be able to clearly identify the pavement markings and signs.

3.5 On-Demand Maintenance

On-demand maintenance activities are used in response to events that are more difficult to predict such as impact damage, concrete spalling, equipment failure, and gaping potholes. This method is also appropriate for the repair or replacement of noncritical items that have minimal impact on tunnel safety and the required service levels. If the impact is potentially significant, appropriate contingency plans should be developed to minimize the adverse effects.

3.5.1 Damage to Tunnel

Among other things, tunnels can be damaged by vehicle collisions, fires, explosions, floods, earthquakes, rock slides, and landslides. After one of these incidents, a damage inspection should be conducted in accordance with the guidelines provided in Chapter 4 of this manual.

3.5.2 Concrete Detachment

Concrete can loosen and detach because of faulty placement techniques, corrosion of rebar, damage from excessive heat, impact from vehicles, and deterioration. Some of these processes may occur without warning. When concrete debris is discovered in the roadway portion of the tunnel, it should be cleaned up immediately; and any loose or dangling concrete should be removed using small hand-held hammers, pry bars, jack hammers, or other appropriate tools.

3.5.3 Sudden Equipment Failure

Equipment failure can be difficult to predict, particularly when electronic components are involved. Appropriate contingency plans should be ready for implementation to restore service as quickly as possible. An effective preventative maintenance program can help reduce the burden placed by on-demand maintenance.

3.5.4 Pavement Repair

Roadway wearing surfaces are typically comprised of concrete or asphalt materials. Sealing cracks and patching potholes are part of roadway maintenance. Extensive subgrade repairs may be needed due to freezing, insufficient drainage, or loss of fines in the subgrade. Pavement repairs should not be allowed to impact the vertical clearances of the tunnel.

3.6 Groundwater Seepage through Liners

Groundwater seepage can be controlled temporarily by interim solutions using catchment troughs and interior composite liners; however, these temporary solutions do not protect the final liner from long-term corrosion and degradation. Before implementing these methods, an engineer should evaluate the potential for:

- Fine soil particle migration, void creation, and redistribution of the stresses around the tunnel liner.
- Fine soil migration, re-deposition, and drain clogging.
- Protection of structural materials from corrosion and further degradation.
- Settlement of adjacent structures because of soil or rock mass dewatering.
- Vehicle strikes due to insufficient clearance of new installed materials.
- Obscuring important safety defects during future inspections of the final liner.

3.6.1 **Catchment Troughs and Pipes**

Troughs may be installed on the inside of the liner to catch leaking water and convey it into the drainage system using interconnected pipes. These systems have made use of neoprene, steel, fiberglass, and flexible or rigid polyvinyl chloride (PVC) pipes in the past; however, some of the plastic type materials are known to release toxic fumes during fires. Simple catchment systems are shown in Figures 3.5 and 3.6. More robust systems are simply sealed better to minimize the chances of water leaks as shown in Figures 3.7 through 3.11. Sometimes radial drainage holes are drilled into the tunnel liner to relieve the water pressure (See Figures 3.12 and 3.13) behind the liner; this water can be collected and conveyed into the drainage system. The buildup of hydrostatic pressures can be relieved somewhat by draining it, which might ultimately reduce the amount of cracking in the tunnel liner.

The size and type of the trough depends on factors such as the severity of the water infiltration problem, the potential for freezing in the winter, the inclination of the cracks, and considerations for fire in the tunnel. The clogging issues can be minimized by cleaning the system and filtering the water. In colder climates, insulation or heating can generally prevent the formation of ice. Small chipping hammers, wire brushes, and high pressure washers are commonly used to remove efflorescence or deleterious materials prior to installation of these systems.

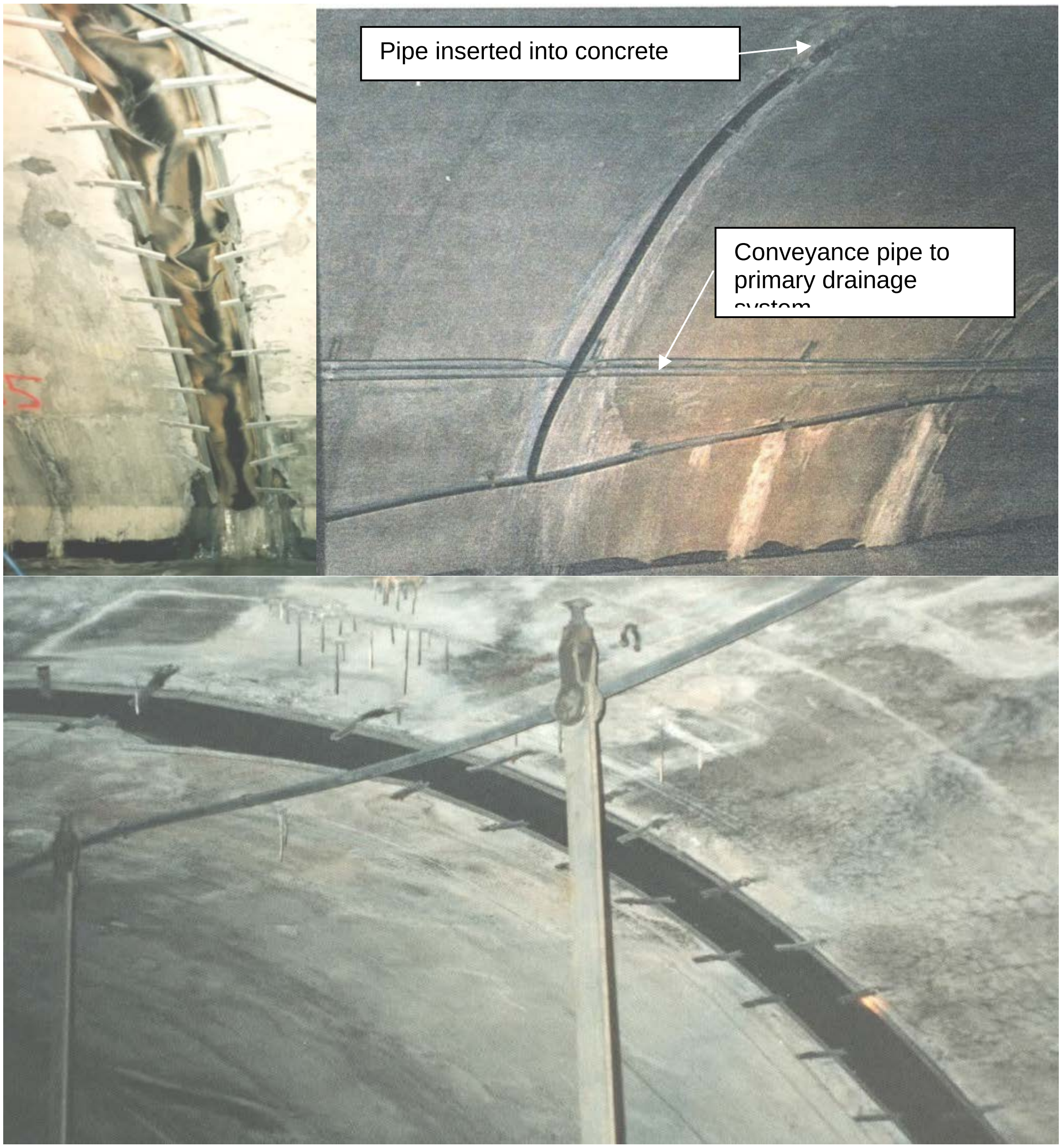

Figure 3.5 – Temporary drainage systems comprised of neoprene rubber troughs and 25 mm (1”) aluminum channels (FHWA, 2005).

The advantages are:

- Easily constructible
- Fairly inexpensive
- Minimal impact on tunnel operations
- Applicable to common types of cracks.

The disadvantages are:

- Some material are unsuitable for fire
- Heating or insulation is required in colder climates
- Water continues to corrode elements.
- The troughs need to be cleaned to prevent clogging.

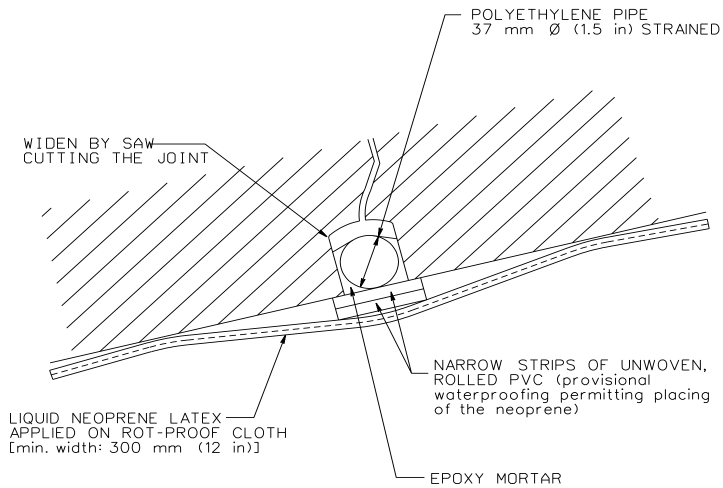

Figure 3.6 – Treatment using membrane covering and pipes (FHWA, 2005).

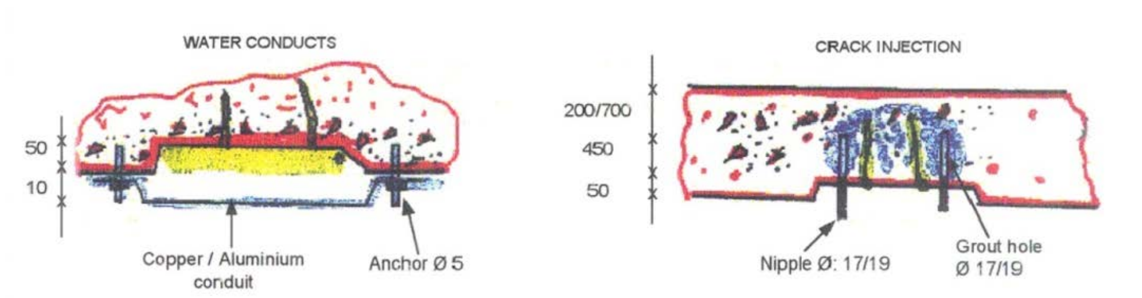

Figure 3.7 – Copper or aluminum conduit along with crack injection used to convey water penetrating a concrete liner (Russell, 2001)

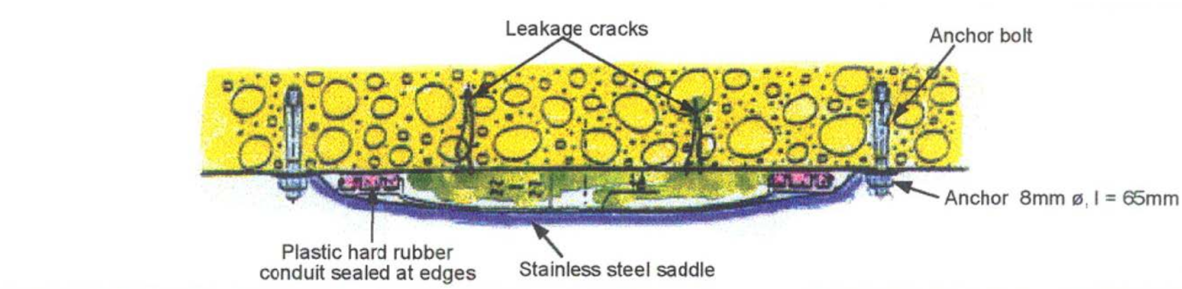

Figure 3.8 – Stainless steel saddle anchored to concrete for conveying water through leakage cracks (Russell, 2001).

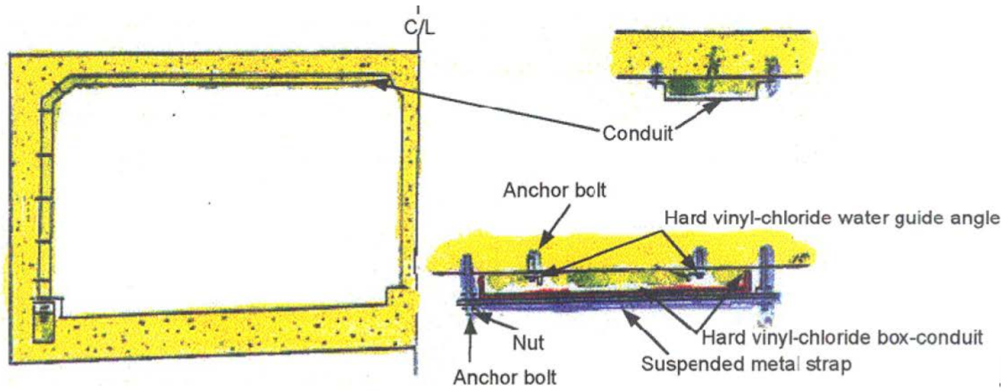

Figure 3.9 – Hard vinyl-chloride box conduit anchored to underside of cast-in-Place concrete roof to convey water leakage (Russell, 2001).

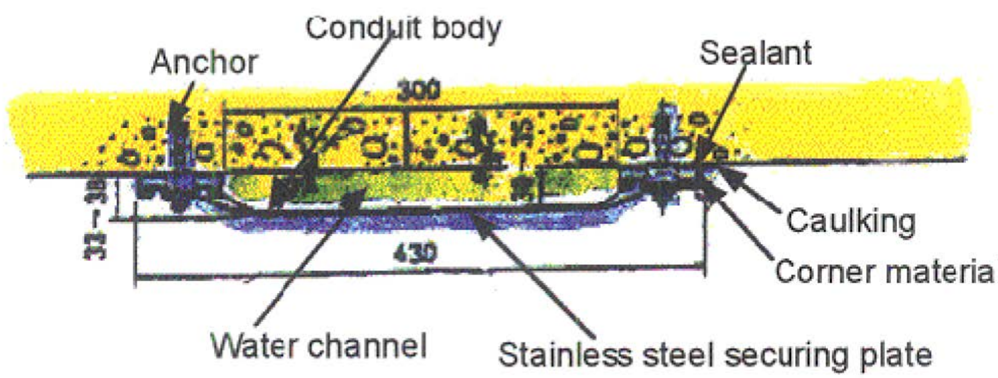

Figure 3.10 – Conduit channel supported by steel securing plate and anchored to concrete roof for conveying water leakage (Russell, 2001)

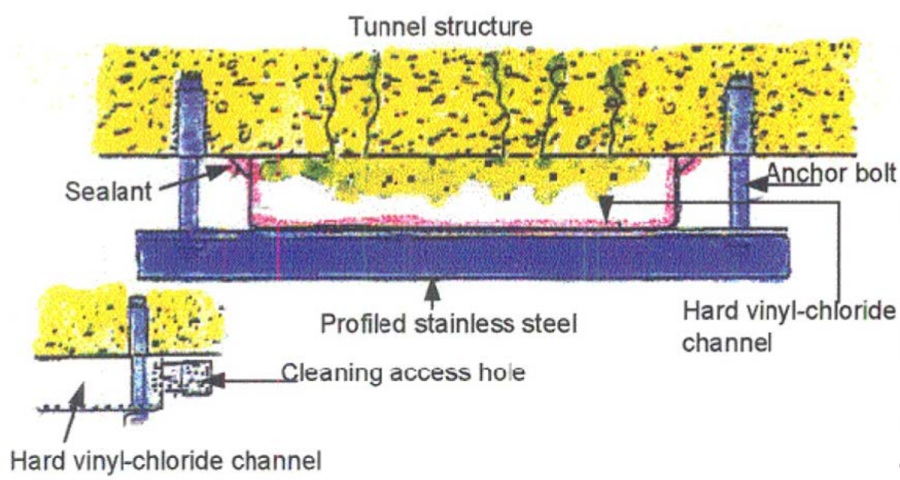

Figure 3.11 – Hard vinyl-chloride channel supported by profiled stainless steel and anchored to concrete roof for conveying leakage (Russell, 2001).

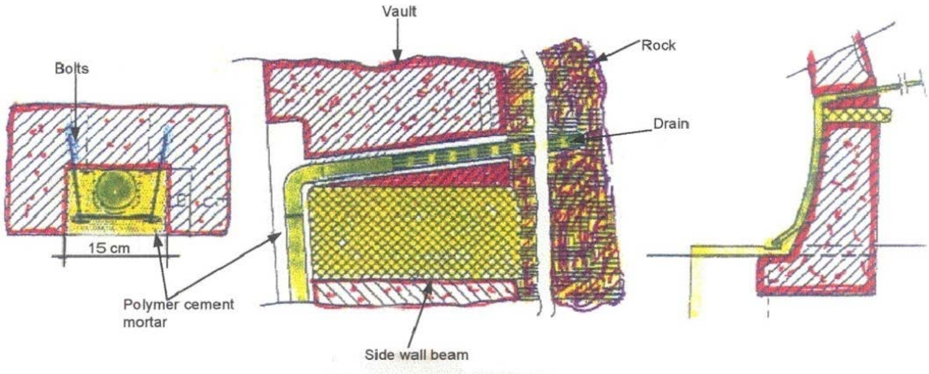

Figure 3.12 – Radial drainage holes drilled through tunnel sidewall to relieve external water pressure. The pipe shown is encased in polymer mortar (Russell, 2001).

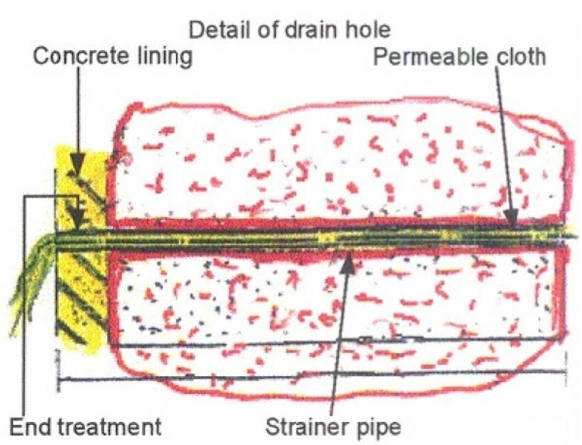

Figure 3.13 – Radial drainage hole drilled through tunnel sidewall to relieve external water pressure. Strainer pipe is wrapped with a permeable cloth to prevent clogging (Russell, 2001).

3.6.2 **Interior Composite Tunnel Liners (NCHRP, 2010; FHWA 2005)**

A composite liner can be constructed on the interior of the tunnel liner to control unwanted seepage. This is achieved by sandwiching an impermeable membrane and geotextile between the existing tunnel liner and a new layer of applied shotcrete (See Figure 3.14). A geotextile is used to protect the impermeable membrane from damage and provide a path for drainage. For more significant drainage, a geo-drain can be used. High Density Polyurethane (HDPE) and Polyvinyl Chloride (PVC) create an impermeable barrier. The application of shotcrete protects the geo-materials against fires. Figure 3.15 through Figure 3.20 depict some common schemes that have been reported in the literature (Russell, 2001).

Prior to installation of the composite liners, the surface areas should be cleaned using small chipping hammers, high velocity water sprayers, or wire brushes. Cracks and joints that leak should first be sealed. Placing a heat-sealed patch over anchorage locations is considered "good practice" to minimize the chances future leaking.

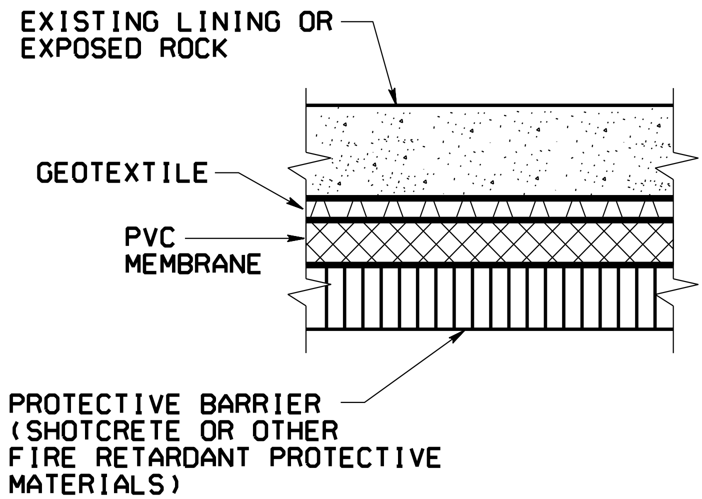

Figure 3.14 – Section of membrane waterproofing system (FHWA, 2005).

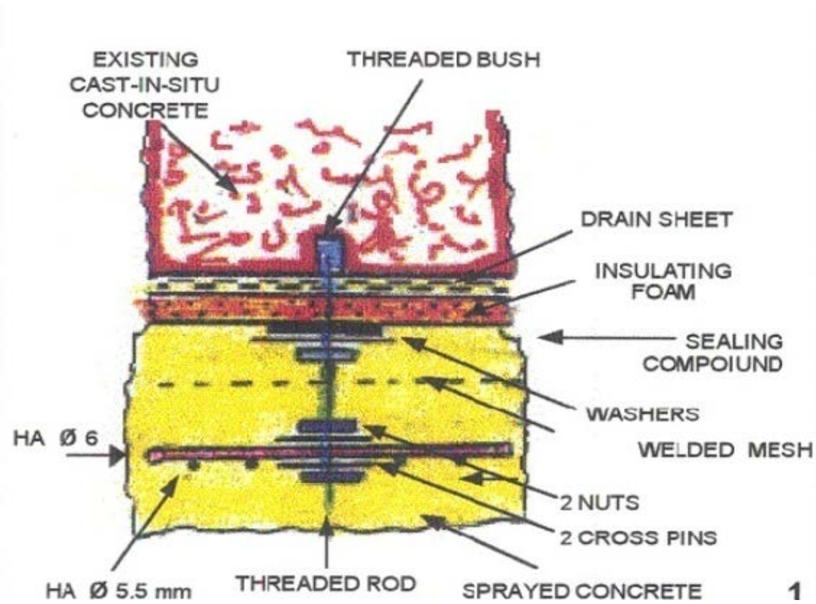

Figure 3.15 – Sealing of leakage water using a drain sheet, insulating foam, and reinforced welded-mesh sprayed concrete. This system is anchored to existing concrete via a threaded rod and nuts/washers (Russell, 2001).

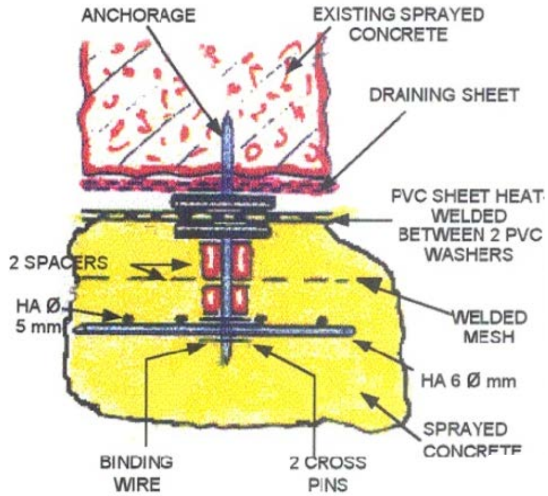

Figure 3.16 – Sealing of leakage water using a drain sheet, PVC sheet heat-welded between washers, and a reinforced, welded-mesh sprayed concrete anchored to the existing concrete surface (Russell, 2001).

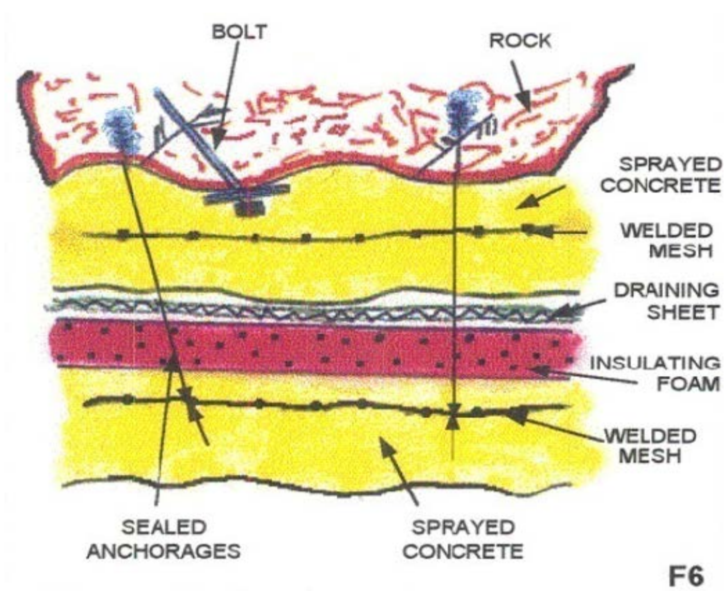

Figure 3.17 – Leakage control in an unlined rock tunnel using a welded-mesh sprayed concrete layer, a drainage sheet, insulating foam, and a protective layer of welded-mesh, reinforced sprayed concrete (Russell, 2001).

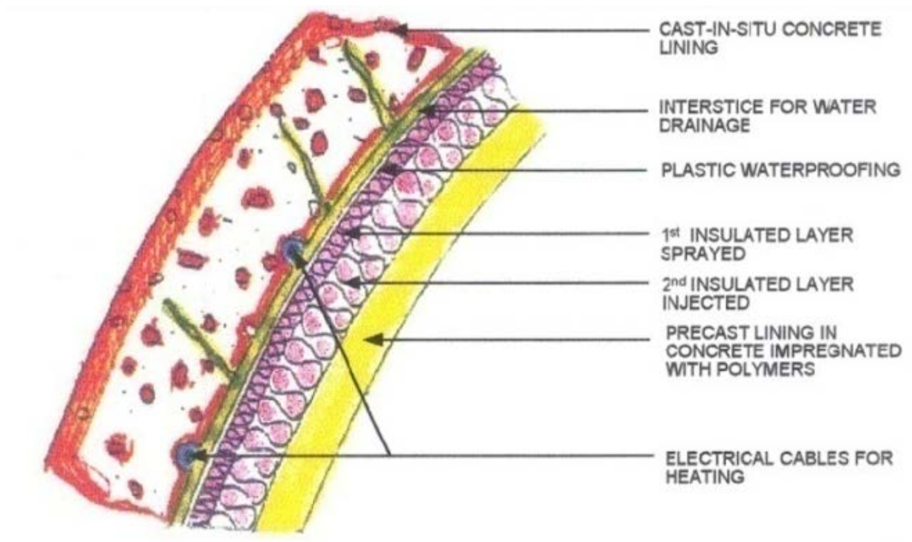

Figure 3.18 – Leakage control on the interior face of an existing concrete tunnel using a space for water drainage, electrical heating cables, plastic waterproofing, sprayed insulating layer, and an interior precast liner (Russell, 2001).

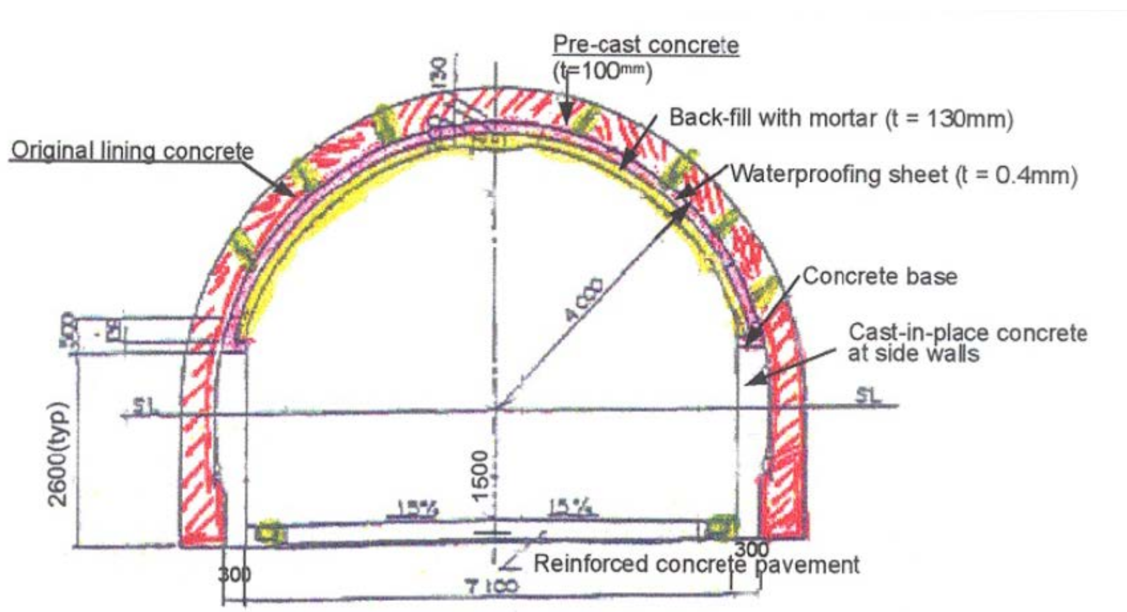

Figure 3.19 – Sealing of leakage water on the interior concrete face by placing a waterproofing sheet and a protective reinforced mortar layer (Russell, 2001).

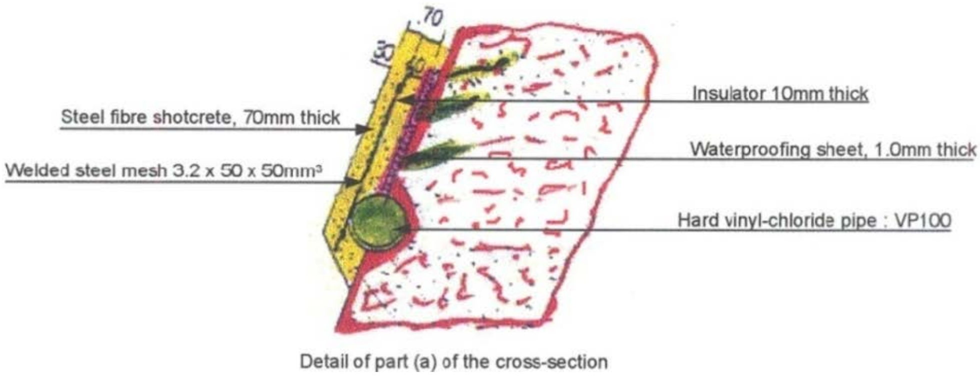

Figure 3.20 – Collecting leakage water via a waterproofing sheet, a vinyl-chloride pipe, and covering with a protective layer of reinforced steel-mesh shotcrete (Russell, 2001).

Water that is circulating can cause negative-side waterproofing sheets to detach. Insufficient anchoring, poor welding, and improper materials are common problems (See Figures 3.21 and 3.22).

Figure 3.21 – Insulated panels under waterproofing membrane in air plenum region above roadway have dislodged in an isolated location (NCHRP, 2010).

Figure 3.22 – Failed installation of waterproofing membrane in air plenum. Note that heat welded attachments did not penetrate the white waterproofing membrane (NCHRP, 2010).

3.6.3 **Exterior Groundwater Barriers**

Exterior groundwater barriers are difficult to install in existing tunnels. When the appropriate provisions are incorporated into the design, some leaking elements can be treated with sealants. In extreme cases, external barriers may be installed to form an impermeable cutoff wall; however, this method is expensive and may not always be feasible. When tunnels are constructed in fractured rock, the discontinuities can be grouted with some success to form an exterior curtain; however with this approach, the leaks are generally "chased" to a new location. Russell (2001) discusses ascending and descending-stage grouting methods.

- Descending-stage grouting is accomplished by drilling the borehole to shallow depths and injecting rock mass with grout starting with the packer near the rock surface. A packer is an expandable membrane that seals the annulus of the borehole between the drill string and the ground to help prevent the grout from leaking out of the borehole. When the first stage is completed, the hole is then drilled deeper to reach the lower areas of the rock. During the second stage, the packer is placed either at the top or bottom of the zone to be treated. Descending-stage grouting is recommended when the rock mass is weak, highly fractured, or otherwise needs to be consolidated before grouting the deeper zones under higher application pressures.
- For ascending-stage grouting, the grout hole is drilled to the full planned depth; and then the grouting is carried out in stages with the packer located at the top of the lowest

grouting stage. For each subsequent grouting stage, the packer should be raised to the next stage and repeated until the grouting is complete in the rock mass.

3.7 Repairs for Structural Concrete

When the concrete has areas impacted by spalling, mortar patches can be applied by hand to patch smaller areas while larger areas are more effectively treated using shotcrete based application methods and economies of scale. When cracks in the concrete need to be repaired, the cracks can be injected with grout. FHWA (2009) and AASHTO (2010) describe these types of repair methods. The links below take the reader to these publications:

- Hand applied mortar patches and shotcrete repairs
    - Surface preparation
        - Chipping hammers
        - Hydro-demolition
    - Treatment of reinforcing steel

http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf#page=513

- Injecting cracks with grout.

  http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf#page=521

3.7.1 **Cementitious Coatings**

Cementitious coatings (See Figures 3.23 and 3.24) can be sprayed onto a moist concrete surface to help reduce its permeability. Maintaining a moist surface will facilitate the formation of chemical bonds with the free lime contained in the substrate concrete and reduce the pore sizes, which tends to inhibit seepage. FHWA (2009) and AASHTO (2010) publications describe methods for applying negative side cementitious coatings:

http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf#page=510

The advantages are:

- Rapid installation
- Minimal disruptions
- Relatively low cost

The disadvantages are:

- Rigid
- Not self-healing
- Sensitive to movement.

Figure 3.23 –View of a cementitious coating applied to the arch (NCHRP, 2010).

Figure 3.24 – Leakage at a construction joint through the cementitious coating (NCHRP, 2010).

3.7.2 **Construction Joints (NCHRP, 2010)**

If the construction joints are leaking, then chemical grout can be injected to seal the joint. Defects such as delaminations and spalls near the joint should be removed and rebuilt with sound materials having properties similar to the concrete substrate. While performing the work, seepage water can be directed into the drainage system using flexible drainage pipe (See Figure 3.25).

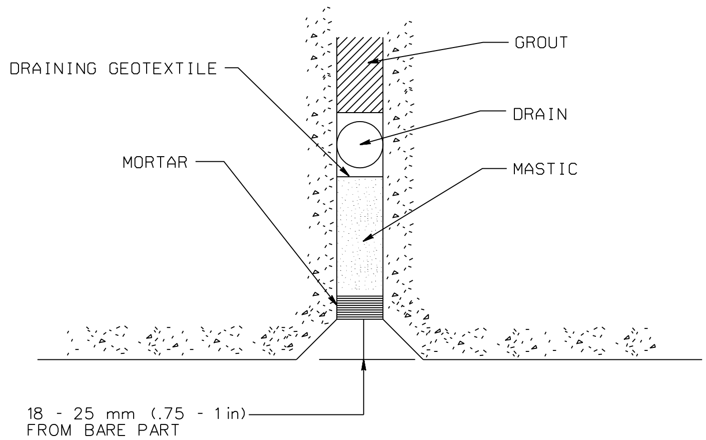

Figure 3.25 – Routing a Construction Joint

3.7.3 **Dry Cracks (NCHRP, 2010)**

"Dry" cracks (generally greater than 1/32" in width) can be repaired on a horizontal surface by damming the edges of the crack and allowing the sealant to penetrate into the crack as indicated in Figure 3.26. Seal the underside of the crack if the epoxy drips through. In all cases the cracks should be cleaned of all loose matter, dirt, and stains using high pressure water or compressed air.

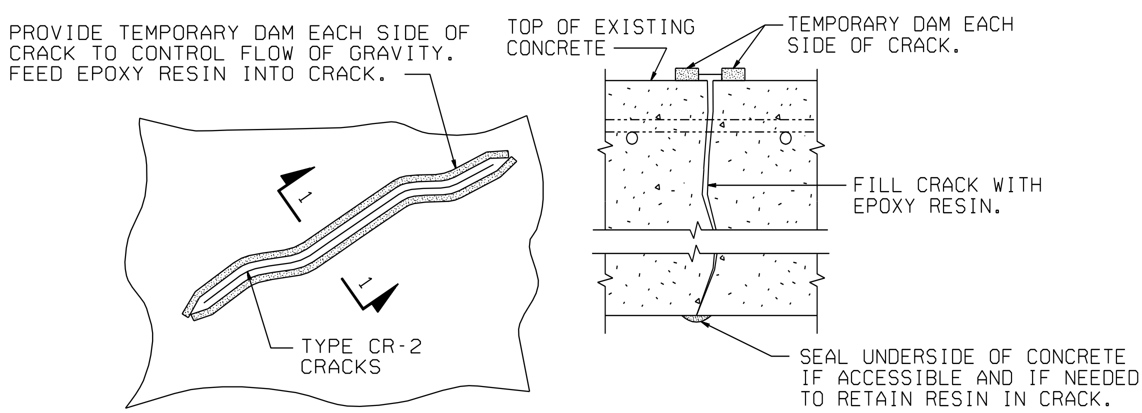

Figure 3.26 – Section 1-1 – horizontal surface crack repair detail (for cracks 0.8 mm (1/32") wide and greater) (FHWA, 2005).

3.7.4 **Re-bonding Delaminated Areas**

Delaminated concrete is characterized by splitting and cracking in a plane that is roughly parallel the surface. Delaminated sections are usually relatively shallow. When a section of delaminted concrete becomes detached from the host element, then it is considered to be spalled. Delaminated areas, such as ceramic tiles, can sometimes be re-bonded using a vacuum injection process (See Figure 3.27).

Figure 3.27 – Vacuum Injection with Methyl Methacrylate (NCHRP, 2010).

3.7.5 **Freeze/Thaw and Salt Penetration (NCHRP, 2010)**

In colder climates, the invert of the roadway may be treated with salt to preclude the formation of ice on the wearing surface, especially near the tunnel portals. The chloride ions in the salt can seep into adjacent concrete structures and accelerate the rate of corrosion in the reinforcing steel, which can lead to spalled concrete or an increased rate of potholes. In older tunnels built before 1950, the concrete was usually batched without air-entrainment admixtures. The natural air-entrainment in these old concrete structures may not be sufficient to adequately resist the damage caused by repetitive freeze/thaw cycles.

3.8 Other Types of Structural Repairs (FHWA, 2009) and (AASHTO, 2010)

The following links take the reader to repair information contained in other documents:

- Segmental liners
  - Precast concrete
  - Steel/Cast iron

  http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf#page=522

- Steel liners
  http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf#page=524

- Masonry liners
  http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf#page=525

- Unlined Rock Tunnels
  http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf#page=525

3.8.1 **Timber Liners**

Timber liners sometimes need periodic treatments to prevent the spread of decay. Some common wood treatments include:

- Boron compounds
- Copper chromium arsenic compounds
- Light organic solvent preservatives or tributyl tin oxide (TBTO).

When the timbers are badly deteriorated, these elements are often encased in shotcrete to preserve the integrity of the liner (See Figures 3.28 and 3.29).

Figure 3.28 – New shotcrete lining over timber supports in rock tunnel. Note timber supports can be seen in the background (NCHRP, 2010).

Figure 3.29 – Interface between timber supports and new shotcrete (NCHRP, 2010).

3.8.2 **Ceilings/Hangers and Anchorages**

Numerous highway tunnels have suspended ceilings for ventilation purposes and, in some cases, aesthetics. These ceilings are usually supported by keyways in the tunnel walls and by hanger rods attached to the tunnel liner, either by means of cast-in-place inserts or post-installed mechanical. Examples are shown in Figure 3.30. See cautionary note below on adhesive (chemical) anchors. Loose or failed adhesive connections should be replaced with mechanical anchors.

FHWA issued a Technical Advisory in 2008 that strongly discourages the use of adhesive anchors for use with permanent sustained loads in tension or overhead applications. The use of anchors in road tunnels should conform to current FHWA advisories and other applicable codes and regulations.

http://www.fhwa.dot.gov/bridge/t514030.cfm

Figure 3.30 – Typical replacement hardware left; undercut mechanical anchors, right.

3.9 Maintenance of Functional Systems

Functional systems include the mechanical, electrical, lighting, fire and life safety, security, sign, and protective systems installed in the tunnel. The equipment rooms for these functional systems, such as the ventilation buildings, pump rooms, and emergency generator rooms, should be kept clean. Remove any debris, grease and oil. Loose debris can damage equipment. All gauges, sight glasses, indicator lights, and safety equipment must be cleaned and checked. Some components might require painting. Movable components should be exercised periodically. Ideally, maintenance programs can be enhanced by collecting data and managing the maintenance activities.

- Computerized maintenance management systems (CMMS) include software that:
  - Generates maintenance, repair, and replacement related work orders
  - Stores historical maintenance, repair, and cost data
  - Analyzes maintenance data (trends) and stores costs
  - Calculates life-cycle costs for individual systems and equipment
- Measurements can be recorded on maintenance logs, checklists, or hand held tablets. Some of the data to be considered for the maintenance management program include the following items:
  - Equipment running hours
  - Ferrous wear particle count in lubricating oils
  - Bearing and drive operating temperatures
  - Vibration of rotating equipment
  - Repair costs of individual equipment

3.9.1 **Maintenance Tools for Functional Systems**

There are many tools that can be used to enhance the maintenance checks for functional systems.

Handheld Infrared Thermometers – Handheld infrared thermometers are useful to spot check the temperature of bearings, drive components, couplings, pipe insulation, steam traps, electrical transformers, and motors. Temperature information is useful for identifying the early onset of problems. Temperature data can also be input into the database for identifying possible problems and trends.

Infrared Thermography – Infrared thermography, or thermal imaging, is useful for identifying a wide range of problems such as:

- Bearing or drive belt/chain friction/wear
- Bearing lubrication contamination; breakdown or conditions of low lubrication levels
- Motor/drive misalignment or pending coupling failure
- Compromised pipe insulation
- Steam trap failure
- Electrical faults

Ultrasonic Testing – Ultrasonic testing uses sound to identify leaking fluids through valves.

Vibration Analysis of Rotating Equipment – Modern vibration measurement instruments (with analysis software) allow for periodic or continuous monitoring of rotating parts. These instruments allow better predictions of potential failures.

Lubrication Sampling and Testing – Use of periodic oil sampling for bearings, drive lubricants, and electrical transformers is helpful for tracking:

- Machine conditions
- Lubrication breakdown/viscosity
- Iron/ferrous wear particles
- Lubricant contamination
- Moisture contamination of lubricant

3.9.2 **Maintenance Certifications for Complex or Dangerous Equipment**

Specialty purpose contractors are often certified to work on certain types of equipment due to inherent dangers. This may be required by local laws and ordinances. Check and comply with the State and local requirements prior to working on:

- Boilers
- Water Heaters
- Pressure Vessels
- Elevators
- CO Monitoring
- Fire Suppression Systems
- Fire Extinguishers
- Fire Standpipes

3.9.3 **Mechanical Systems**

The link below provides the reader to a table of various mechanical components and their suggested maintenance intervals (FHWA, 2005). The table can be used to supplement an existing maintenance program at the discretion of the tunnel owner. *Since the table is generalized, specific and manufacturer recommended maintenance practices should take precedence over the suggestions contained in the table*.

http://www.fhwa.dot.gov/bridge/tunnel/maintman03.cfm#t02

3.9.3.1 **Fans**

Tunnel Ventilation Fans – Since tunnel ventilation fans are critical to the operation of a tunnel and essential for fire and life safety in emergencies, these elements must work when needed (See Figure 3.31). The following items are important maintenance considerations for vent fans:

- Excessive heat and moisture in lubricant are the two leading causes of premature bearing failure.
- Daily inspection and temperature monitoring can be used to help identifying lubrication problems.
- A supplemental lubricant testing program can be used to help validate the maintenance schedule and identify potential problems. The testing should be performed by a certified laboratory using appropriate ASTM and ISO standards.

Figure 3.31 – Mechanical Fan

3.9.3.2 Pumps

There are three broad categories of pumps. These include reciprocating, rotary, and centrifugal. Centrifugal pumps are the most common for tunnel applications. When performing maintenance checks, the motors should be checked for excess temperatures and unusual vibrations. Typically, the pump is controlled by an electrode or float switches in the sump. Examine the check valves and discharge piping.

3.9.4 Electrical and Lighting Systems

Due to issues with worker safety, electrical maintenance and testing should only be performed only by qualified professionals. It is recommended that the staff be certified in Occupational Safety and Health Administration (OSHA) Standards and competent with NFPA Standards *70E: Standard for Electrical Safety Requirements for Employee Workplaces*.

The link below provides the reader to a table of various electrical and lighting components and their suggested maintenance intervals (FHWA, 2005). The table can be used to supplement an existing maintenance program at the discretion of the tunnel owner. *Since the table is generalized, specific and manufacturer recommended maintenance practices should take precedence over the suggestions contained in the table*.

http://www.fhwa.dot.gov/bridge/tunnel/maintman03.cfm#t03

3.9.4.1 Electrical Systems

Electrical components are interconnected and rely on other elements to function properly (Figure 3.32). The InterNational Electrical Testing Association (NETA) produces *Maintenance Testing Specifications (MTS-2007)* that contain detailed information and guidelines about performing maintenance on electrical equipment. The National Fire Protection Association's *NFPA 70B: Recommended Practice for Electrical Equipment Maintenance* is also suggested for incorporation into a tunnel maintenance program.

Figure 3.32 – Electrical system components.

3.9.4.1.1 Cable and Conduit Replacement

Electrical conduit carries electrical wiring and protects it from impact, harsh environments, moisture, chemicals, and corrosives. Depending on their design, conduits often carry a variety of wiring types and sizes. Conduit systems should be inspected to evaluate the effects of corrosion or impact damage. It is possible to repair conduit in the early stages of corrosion, but if the condition worsens, the conduit may need to be removed and replaced. The use of a conduit permits the replacement of cables with minimal disruption to other systems. When junction and pull boxes are a part of an integrated system, the replacement of a cable segment requires much less effort.

3.9.4.1.2 Electrical Conduit Banks

Tunnels often contain many electrical conduits placed on conduit trays. The exterior conduit covering should be checked to ensure that it protects the electrical wires and is solidly mounted. These items should be inspected for signs of impact and other types of damage.

3.9.4.2 **Lighting Systems**

Maintenance programs can be supplemented using information obtained from the ANSI/IES Lighting Handbook. Cleaning should take place periodically. The Luminaire Dirt Depreciation (LDD) factor is a method to account for optimizing the cleaning interval. This method takes into account the degradation of light output on lenses, refractors, lamps, and reflectors due to the accumulation of dirt. Figure 3.33 depicts the maintenance and cleaning of the lighting system.

Figure 3.33 – Tunnel lighting maintenance and cleaning.

3.9.5 **Fire and Life Safety Systems**

The tunnel fire and life safety systems are relatively complex; these systems contain interconnected sophisticated components that function together to enhance safety against fire and smoke (See Figure 3.34). Table 3-4 provides suggested intervals for performing preventive maintenance functions on major pieces of equipment commonly used with fire and life safety systems. *Specific and manufacturers' recommended preventive maintenance procedures should take precedence over the guidelines contained in the table*.

3.9.5.1 **Inspection Certifications**

Equipment and system certifications should be posted at the equipment locations as required. Additionally, it is recommended these certificates be filed and retained. It is common to provide inspection certificates for the following equipment:

- CO Monitoring
- Fire Suppression Systems
- Hydrocarbon Detectors
- Portable Fire Extinguishers

Figure 3.34 – Fire and life safety components.

Table 3-4 – Example Maintenance Intervals for Fire and Life Safety Systems

Fire and Life Safety Systems	Service Interval (1)							
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Bi-Annually	Manufacturer or AHJ (2)
Fire Protection								
Inspect Manual Fire Alarm Boxes			X					
Closed-Circuit TV (CCTV) – Confirm Operation	X							
Automatic Fire Detectors				X				
Fire Extinguishers								
Inspect each fire extinguisher in the tunnel and support spaces				X				
If in a cabinet – Confirm operation of cabinet door – Door must latch securely and open freely				X				
Lubricate door handle and hinges as necessary				X				
Fire Standpipes								
Fire Department Connections Capped and Clear				X				
Confirm threads are undamaged and caps in place				X				
Test flow hydrant				X				
Confirm top nut and caps are tight but not over-torqued				X				
Fire Hydrants								
Grease top nut					X			
Confirm cap's in place					X			
Test flow hydrant					X			
Confirm top nut and caps are tight but not over-torqued					X			
Fire Lines								
Freeze Protection Pumps								
Clean and visually inspect				X				
Lubricate and grease pumps						X		
Heat Tracing – Verify system operation (prior to system operation)						X		
Pipe Insulation with Heat Tracing - Verify condition (prior to system operation)						X		

Fire and Life Safety Systems	Service Interval (1)							
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Bi-Annually	Manufacturer or AHJ (2)
Fire Pumps								
Visually inspect fire pump		X						
Operate pump – Note unusual noises or vibrations				X				
Lubricate pump, motor, and coupling								X
Operate pump and measure current					X			
Check shaft alignment and shaft endplay					X			
Check and correct pressure gauges as required					X			
Measure motor and pump vibration				X				
Fire Pump Controller								
Exercise disconnect switch and circuit breaker		X						
Operate pumps from alternate and primary power supplies		X						
Conduct annual test of system including flow and no flow conditions in accordance with NFPA 72						X		
Fire Tank Fill Pump								
Visually inspect pump		X						
Operate pump – Note unusual noises or vibrations						X		
Lubricate pump, motor, and coupling				X				
Check shaft alignment and shaft endplay				X				
Secondary containment provided for all hazardous materials		X						
MSDS sheets for all materials posted (on file)					X			
Inspect all floors for oil leakage. Add absorbent and clean as required to maintain safe footing	X							
Fire Alarm System								
Perform all tests and inspections in accordance with NFPA 72								
Make and file a permanent record of all inspections and tests conducted								
Open primary power supply to fire alarm panel and note sounding of trouble alarm and light		X						
Perform fire drill by use of drill switch on fire alarm panels, and check that all visual and audible signals emit a sound and tunnel SCADA system (if any) receives alarm		X						

Fire and Life Safety Systems	Service Interval (1)							
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Bi-Annually	Manufacturer or AHJ (2)
Visually inspect all supervisory and water flow alarms on any standpipe systems		X						
Test all heat detectors with a calibrated heat source and replace all failed units					X			
Test all smoke detectors by measuring and recording sensitivity; replace all failed units					X			
Clean all smoke and heat detector housings and check battery voltage under load					X			
Verify that proper alarm devices operate for the appropriate initiating device circuit					X			
Verify that all remote annunciators operate				X				
Check all lamps, alarm devices, and printers for proper operation				X				
Make a discharge test of batteries to determine capacity for operating system for 24 hours					X			
Communications								
Radio	X							
Telephone	X							
Egress								
Emergency Egress		X						
Exit Lighting/Signage/Identification		X						
Tenable Environment (Note: Smoke Control Ventilation is located in Fire Suppression Section)		X						
Emergency Exits		X						
Cross-Passageways		X						
Electrical								
Emergency Lighting			X					
Power			X					

Fire and Life Safety Systems	Service Interval (1)							
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Bi-Annually	Manufacturer or AHJ (2)
Redundant Power			X					
Security Plan			X					
Emergency Response Plan (ERP)								
ERP on File and all Personnel Aware of Requirements					X			
ERP reviewed and update periodically					X			
Tunnel Personnel Training of execution of ERP			X					
Training Exercises with Participating Agencies						X		
Hydrocarbon Detector								
Confirm Hydrocarbon Detector will initiate local and remote alarms								X
CO Monitoring Equipment								
Tunnel (Local) Sensors (Confirm Calibration and/or sensor replacement)								X
Vacuum Tubing (Leak Test)				X				
Vacuum Pump (lubrication)				X				
Central Sensor								X
System Calibration (as required by individual system)								X
Comparison Gas Refill (as required)								X
Life Safety and Fire Code Issues (Flammable/Hazardous Materials)								
All safety guards and covers (belt, chain, electrical panel) in place and secure.		X						
No plastic (PVC, CPVC) pipe located in supply air passages.					X			
All batteries properly stored and vented. Confirm battery charging only taking place in well ventilated spaces.		X						
Flammable material stored in proper containers and properly ventilated spaces.		X						
Secondary containment provided for all hazardous materials		X						
MSDS sheets for all materials posted (on file)					X			
Inspect all floors for oil leakage. Add absorbent and clean as required to maintain safe footing	X							

Fire and Life Safety Systems	Service Interval (1)							
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Bi-Annually	Manufacturer or AHJ (2)

Notes:

(1) The above table is intended as a guide. In all cases, maintenance should be performed in accordance with the manufacturer's specific recommendations.

(2) Perform in accordance and as recommended in unit manufacturer's literature or inspect on an interval required by the local authority having jurisdiction (AHJ).

3.10 Signs and Communication Devices

Tunnel facilities contain several different types of signs, including exit and entry signs for ramps, speed limit signs, variable message signs, and emergency egress signs for motorists who may need to evacuate on foot in case of a fire event. Routine maintenance is required to ensure attachment hardware is intact (bolts are tight, bolts are embedded properly, and the anchorage to the foundations is crack free), dirt accumulation is removed to maintain visibility and reflectivity, and burnt out bulbs are replaced.

3.11 Corrosion Protection Systems

Corrosion protection systems include coatings (e.g., epoxies, powder coatings, paint or galvanizing), high-density concrete cover, tunnel finishes (e.g., tiles, metal panel, or coatings), and cathodic protection systems.

Protective coatings are usually sprayed-on epoxy paint or cementitious coatings over bare concrete surfaces. Epoxy paint provides good reflectivity off the tunnel ceiling and walls, brightening the tunnel environment and improving safety. Vehicle exhaust and overspray will dull these epoxy coatings, causing them to lose reflectivity. Regularly scheduled washing will restore reflectivity; however, numerous washing cycles will eventually degrade these coatings to a condition that necessitates repair or complete reapplication.

Cathodic protection systems are comprised of a sacrificial material (anode) to protect the primary metal from corrosion. In highly corrosive environments, an electrical current is induced in the material to force corrosion to occur in the sacrificial anode. If an impressed current is used to protect the reinforcing steel, periodic maintenance and inspection of the system is necessary to ensure that the system is working as designed.

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National Fire Protection Association (NFPA) – NFPA 14, *Standard for the Installation of Standpipes and Hose Systems.*

National Fire Protection Association (NFPA) – NFPA 72, *National Fire Alarm and Signaling Code.*

National Fire Protection Association (NFPA) – NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways.*

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TOMIE MANUAL

CHAPTER 4

INSPECTION

Chapter 4 - Inspection

4 Inspection

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

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

The NTIS can be obtained from the Federal Registrar using the link below:

https://www.federalregister.gov

4.1 Tunnel Operations Maintenance Inspection and Evaluation Manual

This manual is a resource for developing comprehensive operations, maintenance, inspection, and evaluation programs for highway tunnels. This chapter focuses on the inspection of highway tunnels, but all of the other chapters in this manual are also relevant as follows:

Chapter 1 contains background information regarding the development of the NTIS. This chapter also reviews the fundamentals of highway tunnels including tunnel construction methods and shapes, liner types and finishes, slabs and wearing surfaces, and tunnel systems such as drainage, ventilation, lighting, power, and communication.

Chapter 2 discusses the operation of highway tunnels such as general staff organization, responsibilities, and duties; normal operating procedures; and response to emergency conditions.

Chapter 3 presents information on maintenance of highway tunnels such as causes of deterioration, maintenance strategies, repair techniques, and guidelines for maintenance of structural, civil, and functional systems.

Chapter 4 focuses on developing safety inspections for highway tunnels. Some of the essential requirements of the NTIS are summarized to include the responsibilities of the tunnel inspection organization, qualifications of inspection personnel, inspection procedures and practices, and the different types of tunnel inspections. This chapter also explores health and safety issues for inspectors, inspection equipment, typical tunnel defects, owner defined elements, critical findings, and condition ratings. This chapter concludes with a glossary of selected terms and a list of references.

Chapter 5 discusses the evaluation of tunnel inspection findings; and it presents techniques for obtaining additional information to perform an evaluation, strategies for evaluating defects, and methods of load rating tunnels.

4.2 Specifications for National Tunnel Inventory (SNTI)

The SNTI contains the requirements for coding and reporting inventory and inspection data to be submitted to the FHWA as part of the National Tunnel Inventory (NTI). This data will allow tunnel owners, the FHWA, and the general public to attain information on the condition of highway tunnels in the United States.

The inventory data contains items that are used for tunnel identification such as age, service classification, geometric data, load rating and posting, navigational clearances, and structural type. This data can be obtained from existing records and field verified as needed. The data must be collected and submitted in accordance with the NTIS.

The SNTI includes instructions for recording the condition states of tunnel structural, civil, and functional systems. Structural elements include liners, roof girders, columns, 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. Civil elements include wearing surfaces, traffic barriers, and pedestrian railings. Functional systems include the mechanical, electrical, lighting, fire and life safety systems, security equipment, signs, and protective finishes.

4.3 Tunnel Inspection Organization

In accordance with the NTIS, all State, Federal Land, and Tribal governments with one or more tunnels in their jurisdiction are required to establish a tunnel inspection organization. A suitably qualified program manager should take charge of the tunnel inspection program for the responsible jurisdiction and ensure that the requirements of the NTIS are fulfilled.

4.3.1 Responsibilities

The tunnel inspection organization is responsible for developing and maintaining inspection policies and procedures within their jurisdiction. Tunnel specific inspections, functional system tests, and critical system checks should be included in these procedures. Critical findings should be reported and corrected in a timely manner. Some of the responsibilities of the tunnel inspection organization include:

- Establishing written policies and procedures.
- Maintaining tunnel inventory and inspection data.
- Regularly reporting NTI data to the FHWA.
- Maintaining qualification records of personnel including national inspector certification.
- Establishing an effective quality control and quality assurance program.

The tunnel inspection organization collects and maintains tunnel inventory and inspection data, addresses critical findings, and maintains a registry of nationally certified tunnel inspectors within their jurisdiction. Reports and electronic files should be generated to document the actions taken in response to the inspection findings. Health and safety procedures are needed to protect the inspection team, tunnel facility personnel, and the users of the tunnel facility.

Quality control and quality assurance programs are used to promote accuracy, ensure consistency, facilitate improvement, and help maintain a high level of reliability. Periodic field reviews of inspection team and their work, quality checks on data, and independent reviews of the inspection results should also be part of the program. The use of checklists is recommended practice. Quality control refers to observations, monitoring, and performance testing to maintain the quality of the tunnel inspections and load ratings; these practices are usually performed continuously by the teams performing the work. Quality assurance is associated with a systematic approach to improve the overall program effectiveness, verify the accuracy of the quality control procedures, and ensure that established standards are met; these procedures are performed independent of the inspection and load rating teams performing the work.

Qualified individuals are needed to carry out the tunnel inspections. The program manager is responsible for the overall inspection program and leads the tunnel inspection organization. Team leaders supervise other subordinate inspection team members, oversee the inspection in the field, and report to the program manager. Team leaders are responsible for data collection and reporting. The tunnel inspection organization is responsible for establishing a certification registry for tunnel inspectors. Each practicing tunnel inspector should be identifiable within the appropriate jurisdiction using a unique identification such as numbering system that correlates an individual inspector with a specific certification record.

When a tunnel is complex, a professional engineer is needed to determine whether special procedures, increased training, or additional qualifications and experience are necessary to lead the inspection. In accordance with the NTIS, the type of construction, functional systems, history of performance, and the physical and operating condition of the tunnel should be considered when determining the inspection requirements for complex tunnels.

Tunnels should be load rated in accordance with the NTIS after an inspection, as appropriate, to determine the safe vehicular load carrying capacity for the roadway. The load rating analysis must be performed by a qualified professional engineer. Tunnels must also be posted or restricted, as appropriate, after conducting the load rating in accordance with the NTIS.

4.3.2 **Planning and Scheduling**

The planning and scheduling of an inspection includes understanding the requirements of the NTIS, reviewing existing tunnel records, coordinating with appropriate tunnel facility personnel, developing health and safety plans, procuring safety and inspection equipment, reviewing defects common to tunnels, identifying the need for owner defined elements, and developing forms and reports for carrying out the inspection. When appropriate, tunnels must also be load rated. A detailed inspection schedule and work plan should address all of the critical aspects.

The NTIS contains the requirements for inspection personnel, inspection procedures, types of inspections, and the inspection interval. To ensure familiarity with tunnel inspection techniques and practices, the FHWA developed a comprehensive training course for the national certification of tunnel inspectors. Alternate training, that meets FHWA's approval, may be substituted for this tunnel inspection course as mentioned in the NTIS.

The inspection program must be developed sufficiently to be capable of evaluating the tunnel elements and identifying any safety or structural concerns. A successful inspection plan should anticipate the potential problems, streamline processes, and enhance the early detection of defects. Once the overall plan has been developed, the supplementary details for each specific inspection task should be described in detail. The need for specialists to test or inspect any sophisticated components in the tunnel should be evaluated along with the need to disassemble and clean any parts or equipment. The tools and equipment necessary for the job must also be provided. For example, when the bearings of a small motor need to be disassembled and inspected in a dark room, the parts can become lost. In additional to any safety precautions to be implemented, the procedures should address additional lighting, storage of small components, and on-site availability of spare parts for this example.

A pre-inspection visit of the tunnel facility is needed to prepare for the inspection. The general tunnel configuration, current site conditions, methods of access, and traffic conditions must be understood. Areas with access difficulties should be identified so that inspection procedures can properly address these issues. Non-destructive testing, robotic video inspection, and access equipment should be considered. The inspection team should prepare as-built sketches, diagrams, and schematics of electrical, mechanical, and hydraulic systems for use during the inspection.

Health and safety consideration should be evaluated. Coordinate with local and state police, fire departments, ambulatory, and medical services in advance, particularly when dealing with confined space. OSHA requires that a competent person makes frequent and regular inspections of the job sites, materials, and equipment during the course of hazardous work. The term "Competent Person" is used in many OSHA standards and documents. An OSHA "competent person" is defined as "one who is capable of identifying existing and predictable hazards in the surroundings or working conditions which are unsanitary, hazardous, or dangerous to employees, and who has authorization to take prompt corrective measures to eliminate them".

4.3.3 **Reviewing Existing Tunnel Records – Tunnel File**

The available records at each tunnel facility need to be thoroughly reviewed and evaluated prior to conducting an inspection. Important records that are normally part of the tunnel file include the construction plans, shop drawings, working drawings, as-built drawings, specifications, cost-estimates, correspondence, photographs, material certifications, material test data, and load test data. The history of the operating, inventory, maintenance, inspection, and repair records should also be reviewed. Check for accident records, posting, and permit loads. The goals should be to identify problem areas, formulate appropriate inspection procedures, check assumptions, verify schedules, and develop inspection documents including forms, survey control, and sketches.

The review process might involve sorting through a large number of documents, determining which records are relevant, searching multiple locations or facilities, and resolving conflicts including different formats, measuring units, or stationing. Processes should be developed to preserve the integrity of the existing file records, which can be difficult or impossible to replace. For complex tunnels considerable time and effort may be needed to prepare sketches, electrical, mechanical, or hydraulic schematics, or other pertinent details for the inspection.

4.3.4 **Coordinating with Personnel at the Tunnel Facility**

The tunnel inspection organization must coordinate with the tunnel facility to be inspected to ensure a safe and efficient environment. If critical findings are discovered during the course of an inspection, the appropriate personnel must be immediately notified. As such, communication protocols should be clearly established in advance of the inspection.

Prior to conducting the inspection, the inspection team and tunnel facility personnel should agree on various protocols such as access to the tunnel, health, and safety provisions, equipment staging areas, equipment shutdowns, maintenance of traffic, lane closures, inspection times, and the use of parking facilities. Enclosed spaces like the upper plenum, the fan room, the electrical room, or other such miscellaneous space may need special entry procedures. For example, to test the air flow velocities due to different fan speeds in the plenum, the inspector should coordinate with the tunnel operator to run the fans through all the various settings.

Equipment may need to be operated during the inspection process. Precautionary measures can be implemented to prevent injury to inspectors, tunnel personnel, and motorists. Coordination is necessary when removing equipment from service. This includes powering off, locking out, and tagging-out fans, motors, or other energized equipment as well as testing the power and control systems to validate the procedures. Proper lock-out/tag-out procedures must be implemented.

Communicate with the staff at the tunnel facility to learn if there are any unresolved or lingering problems. If possible, the inspection team should speak with the staff about recent repairs, maintenance schedules, unusual noises, problems, or impact damage. Tunnels that are difficult to access may require assistance or advise from the tunnel facility staff.

4.4 Tunnel Inspection Personnel

The program manager and the team leader are specifically identified in the NTIS; other inspection personnel have been discussed in this chapter to include discipline specific specialists and field inspectors. At the owner’s discretion, specialized contract inspectors may be used to assist with complicated or sophisticated tunnel systems. Table 4.1 identifies the typical positions on an inspection team. In accordance with the NTIS, an independent assessment is desired; therefore, the operating and maintenance personnel should not be used for inspection purposes.

Table 4.1 – Inspection Team Members

Team Members	Role	Qualifications
Program Manager	Overall in charge of the inspection program	Mandated
Team Leader	Leads and coordinates inspections in the field	Mandated
Discipline Specialist	Performs inspection of specific systems and elements	Recommended
Inspectors	Assists the team leader and discipline specialists	Recommended
Specialty Contractor	Inspects complex components and electronic systems	Recommended

4.4.1 **Program Manager**

The program manager is the individual in charge of the tunnel inspection program for a State, Federal Land, or Tribal government that has one or more tunnels within their jurisdiction. This person must be capable of leading the tunnel inspection organization and ensuring that the requirements of the NTIS are fulfilled. The program manager may delegate duties and responsibilities to qualified delegates who take charge of a particular subset of tunnels; however, the program manager for the jurisdiction remains responsible for ensuring compliance.

On behalf of the tunnel inspection organization, the program manager develops written procedures, schedules inspections, procures inspection and safety equipment, coordinates with tunnel facility staff, and advises the team leader as necessary. Ideally, the program manager should have a general understanding of all aspects of tunnel engineering including design, construction, operation, maintenance, inspection, evaluation, load rating, and rehabilitation. Good judgment is essential for this position in order to respond appropriately to safety and structural concerns within the tunnel.

Refer to the NTIS for the complete requirements of this position. The program manager must be a registered professional engineer or have at least 10 years of tunnel or bridge inspection experience. This individual must also be a nationally certified tunnel inspector, which requires comprehensive training, end-of-course assessment, and periodic refresher training.

4.4.2 **Team Leader**

The team leader is the person on-site who is in charge of the inspection team. This person is responsible for inspection planning, preparing, performing and reporting to include coordinating the field work. The team leader is responsible for evaluating the deficiencies, quality checking of the inspection data, and making sure that the inspection reports are complete, accurate, and legible. The team leader should also conduct safety briefings as needed. The team leader should be able to provide recommendations for the repair of defective items and must initiating appropriate actions when critical findings are discovered.

Refer to the NTIS for the complete requirements. A team leader must be a nationally certified tunnel inspector. Additionally, the team leader is expected to meet at least one of the following:

- Registered professional engineer and at least 6 months of tunnel or bridge inspection experience.
- 5 years of tunnel or bridge inspection experience.
- Appropriate combination of education and experience as described in the NTIS.

In addition to the minimum requirements stated above, the team leader should be a professional engineer when the tunnel is complex or if it has distinctive features or functions. Team leaders must be on site at all times for initial inspections, routine inspections, and in-depth inspections.

4.4.3 Inspection Assistance from Discipline Specific Specialist and Field Inspectors

The inspection team should consist of a minimum of two individuals to carry out the field work in a balanced and efficient manner. Discipline specific specialists and trained field inspectors should assist with the inspections as necessary. These individuals on the inspection team should:

- Be knowledgeable of tunnel components and understand their function.
- Be able to climb and/or use equipment to access various areas of the tunnel.
- Be able to use equipment or apply appropriate test methods.
- Be able to print legibly and draw accurate sketches.
- Be able to read and interpret drawings.
- Be able to use appropriate technology as required for data collection.

Discipline Specific Specialists – When complex civil/structural, mechanical, or electrical systems need to be inspected, the team leader should assign discipline specific specialists with suitable training and experience to help conduct these inspections. Ideally, these specialist individuals should be registered professional engineers or at least engineers-in-training.

A) Civil/structural specific inspectors should ideally have the following education, training, and experience:

- Be a nationally certified tunnel inspector.
- Have tunnel or bridge inspection experience with the ability to identify and evaluate defects that diminish the integrity of a structural member.
- Have design experience and be familiar with the type of civil/structural systems installed in the tunnel. Examples of these systems include, but are not limited to:
    - Liners
    - Roof girders, ceiling girders, and invert girders
    - Columns/piles
    - Cross passageways
    - Interior walls
    - Portals
    - Ceiling slabs, invert slabs, and slabs on grade
    - Hangers and anchorages
    - Ceiling panels
    - Joints
    - Wearing surfaces
    - Traffic barriers
    - Pedestrian railings
- Be able to assess the degree of deterioration for concrete, steel, masonry, and timber materials.
- Be aware of the applicable codes and guidelines for structural systems.

B) Mechanical specific inspectors should ideally have the following education, training and experience:

- Be a nationally certified tunnel inspector.
- Have tunnel or bridge inspection experience with the ability to evaluate physical and operational conditions of mechanical systems and equipment.
- Have design experience or be familiar with the type of mechanical systems in tunnels. Examples of these systems include, but are not limited to:
  - Tunnel ventilation
  - Air conditioning
  - Heating
  - Control units
  - Plumbing
  - Tunnel drainage and pumping systems
  - Emergency generators
  - Fire Protection
  - Wells/Septic
  - Flood gates
- Be aware of applicable codes and guidelines for mechanical features.

C) Electrical specific inspectors should ideally have the following education, training, and experience:

- Be a nationally certified tunnel inspector.
- Have tunnel or bridge inspection experience with the ability to evaluate the physical condition, as well as the operational condition of the electrical systems and equipment.
- Have design experience or be familiar with the type of electrical systems installed in tunnels. Examples of these systems include, but are not limited to:
  - Power distribution.
  - Emergency power.
  - Lighting.
  - Emergency lighting.
  - Fire detection.
  - Air-quality monitoring.
  - Cameras and safety systems.
  - Communications.
- Be aware of applicable codes and guidelines for electrical systems to include:
  - NETA MTS-2011 – InterNational Electrical Testing Association (NETA), Maintenance Testing Specifications—developed for those responsible for the continued operation of existing electrical systems and equipment to guide them in specifying and performing the necessary tests to ensure that these systems and apparatus perform satisfactorily, minimizing downtime and maximizing life expectancy.
  - NFPA 70 – National Fire Protection Association 70 – covers installations of electric conductors and equipment within or on public and private buildings or other structures, installations of conductors and equipment that connect to the

supply of electricity, installations of other outside conductors and equipment on the premises, and installations of optical fiber cables and raceways.
- NFPA 70B – National Fire Protection Association 70B – recommended practice for electrical equipment maintenance for industrial-type electrical systems and equipment, but is not intended to duplicate or supersede instructions that electrical manufacturers normally provide.
- NFPA 70E – National Fire Protection Association 70E – addresses those electrical safety requirements for employee workplaces that are necessary for the practical safeguarding of employees.
- NFPA 72 – National Fire Protection Association 72 – national fire alarm code that covers the application, installation, location, performance, and maintenance of fire alarm systems and their components.
- NFPA 502 – National Fire Protection Association 502 – covers fire protection and fire and life safety requirements for limited access highways, road tunnels, bridges, elevated highways, depressed highways, and roadways that are located beneath air-right structures.
- ITA Guidelines for Structural Fire Resistance for Road Tunnels – International Tunneling Association (May 2004) – covers guidelines for resistance to fire for road tunnel structures.
- IES LM-50 – Illuminating Engineering Society, Lighting Measurements–50 – provides a uniform test procedure for determining, measuring, and reporting the luminance characteristics of roadway lighting installations.
- IES RP-22 – Illuminating Engineering Society, Recommended Practices–22 – provides information to assist engineers and designers in determining lighting needs, recommending solutions, and evaluating resulting visibility at vehicular tunnel approaches and interiors.

Field Inspectors – Field inspectors assist the team leader and discipline specific specialists carry out the inspection work. Some duties of the inspector include carrying inspection equipment, filling out inspection forms, taking photographs, and making sketches. The NTIS does not mandate specific qualifications for field inspectors; however, the following qualifications are recommended for field inspectors assigned to civil/structural, mechanical, and electrical inspection work. Ideally, the field inspectors would have an engineering background with education, training, and experience within their respective fields of practice.

A) Civil/structural field inspectors ideally should:
- Be a nationally certified tunnel inspector.
- Be trained in general civil/structural inspection requirements.
- Have tunnel or bridge inspection experience with concrete, steel, timber, and masonry structures.
- Design and maintenance experience is also useful.

B) Mechanical field inspectors ideally should:
- Be a nationally certified tunnel inspector.
- Be trained in general mechanical inspection requirements.

- Have inspection experience with mechanical and plumbing systems.
- Design and maintenance experience is also useful.

C) Electrical field inspectors should:
- Be a nationally certified tunnel inspector.
- Be trained in general electrical and electronic inspection requirements.
- Have inspection experience with electrical systems.
- Design and maintenance experience is also useful.

4.4.4 **Specialty Contractors**

Specialty contractors are beneficial when the regular inspection staff lacks the specialized skills and experience necessary to inspect sophisticated equipment or complex systems such as power distribution systems, fire protection and detection systems, security systems, and SCADA systems. It is advisable to use qualified specialty contractors when inspecting complex units that pose elevated risks to safety such as boiler units, electrical systems, or energized equipment like transformers. This may help to minimize health and safety risks to the inspection crew and prevent damage to very expensive equipment.

Electrical and Electronic Inspectors – To inspect elements with advanced electronic circuitry, the staff furnished by the specialty contractors should have the following education, training and experience:
- Certification by an organization meeting the requirements of the International Electrical Testing Association (NETA); or
- All of the following qualifications:
    - Be nationally recognized as an electrical testing laboratory.
    - Be regularly engaged in the testing of electrical systems and equipment for the past five years.
    - Have at least one professional engineer on staff that is licensed in the State where the work is being done.
    - Have in house or lease sufficient calibrated equipment to do the testing required.

Boiler Inspector – To inspect boilers, boiler room, and pressure vessel located within the tunnel facility, the staff furnished by the specialty contractors should be:

- Listed as an authorized inspection agency by the National Board of Boiler and Pressure Vessel Inspectors; and certified for boiler and pressure vessel work by an organization meeting the requirements of the American Society of Mechanical Engineers (ASME).

4.5 Inspection Procedures

Inspection procedures are the written documentation of policies, methods, considerations, criteria, directions, and other conditions for planning and conducting tunnel inspections. Written procedures are used enhance the overall effectiveness of the tunnel inspection program and to formalize the inspection process. Procedures should be developed to ensure that adequate planning and scheduling takes place prior to conducting the inspection. Written procedures should describe the requirements for:

- Inspection documentation, forms, and reports; see Section 4.12 of this Manual.
- Record keeping and documentation requirements.
- Planning and scheduling to include unique structural or functional system characteristics.
- Inspection "best practices" and inspection techniques; see Section 4.9 of this Manual.
- Requirements for functional system testing, direct observation of critical system checks, and testing documentation.
- General, tunnel-specific, and specialized instructions.
- Specialized procedures, training, and experience for complex tunnels.
- Components to disassemble or clean.
- Measurements and survey control.
- Use of current technology and practices.
- Annual reports to FHWA.
- Addressing critical findings and reporting to FHWA within 24 hours.
- Load rating, posting, and restricting as appropriate for evaluating safe vehicle load.
- Maintenance and protection of traffic during the inspection.
- Parking and staging areas during the inspection.
- Quality assurance and quality control implementation plans.

Inspection procedures need to address the various types of tunnel inspections and define the roles and responsibilities of those performing the inspection to include the team leader. Staff should be used that are not associated with operation or maintenance of the tunnel structure or functional systems. General and tunnel specific tunnel inspection procedures add value to the overall inspection program and help ensure compliance with all of the regulatory requirements. The results will be more accurate with more consistent findings. Inspection procedures convey:

- Important design assumptions for tunnel and account for complexity of tunnel systems.
- Health and safety instructions including emergency response and enforcement rules.
- Composition of inspection team and qualifications of personnel including training, certification, registration, and licensure requirements.
- Communication and reporting protocols.
- Inspection tools and safety gear.
- Use of diagrams, photos, and sketches.

Inspection procedures need to be clearly stated, easily understood, and concisely written. The procedures should reflect the complexity of the structural, civil, and functional systems of the tunnel. See owner defined elements for geotechnical considerations of tunnels that cross navigation channels. Ensure that the procedures identify the:

- Structural elements and functions systems.
- Methods of inspection.
- Frequency of inspection for each inspection method.
- Inspection equipment, access equipment, safety equipment, and traffic coordination.
- Practices to identify and record deficiencies in accordance with the SNTI.

Inspection procedures are needed for discovery of critical structural or safety related deficiencies found during the inspection of the tunnel. The procedures should incorporate the following steps, as deemed appropriate:

- Immediate critical deficiency reporting steps.
- Emergency notification to the police and the public.
- Rapid evaluation of the deficiencies found.
- Rapid implementation of the corrective or protective actions.
- A tracking system to ensure adequate follow-up actions.
- Provisions for identifying other tunnels with similar structural or functional system defects for follow-up inspections.

4.5.1 **Inspection Practices**

The tunnel inspection organization should develop a set of best practices to help maintain the quality of the tunnel inspection program. Some 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 better observe the condition of the defect. 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; while 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 once it has been documented. A survey control system helps to 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 that have 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.

In addition to locating a defect by panel number and station in the longitudinal direction of the tunnel, the position of the defect within the tunnel cross-section (perpendicular to the tunnel axis) should be recorded. Figures 4.1 to 4.4 show some schemes that have been used successfully for locating defects. The direction to face must be established. For example, a defect in a circular tunnel located at 4 o'clock facing in the direction of traffic would be at 8 o'clock when facing against the direction of traffic. The areas of horseshoe, rectangular, and other shaped tunnels can be divided into convenient sections that uniquely define the location such as the top, left, right, or bottom. For example, a defect in a rectangular tunnel at Station 10+55.33 may be written as "located 3.5 feet up from the bottom right wall when facing up-station" or abbreviated as "3.5BRW/US@10+55.33".

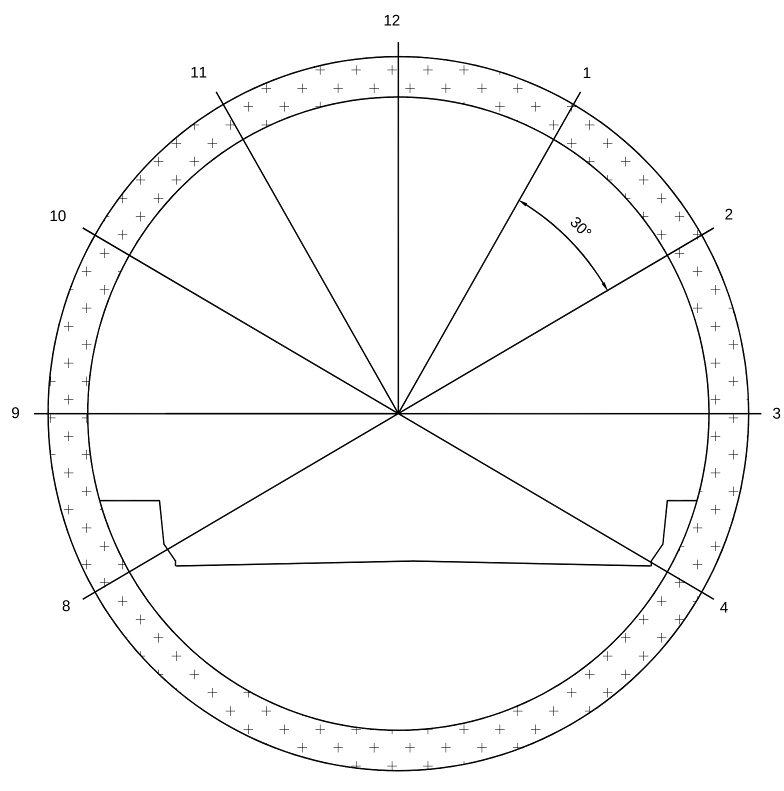

Figure 4.1 – Sample clock system designations used with circular tunnel.

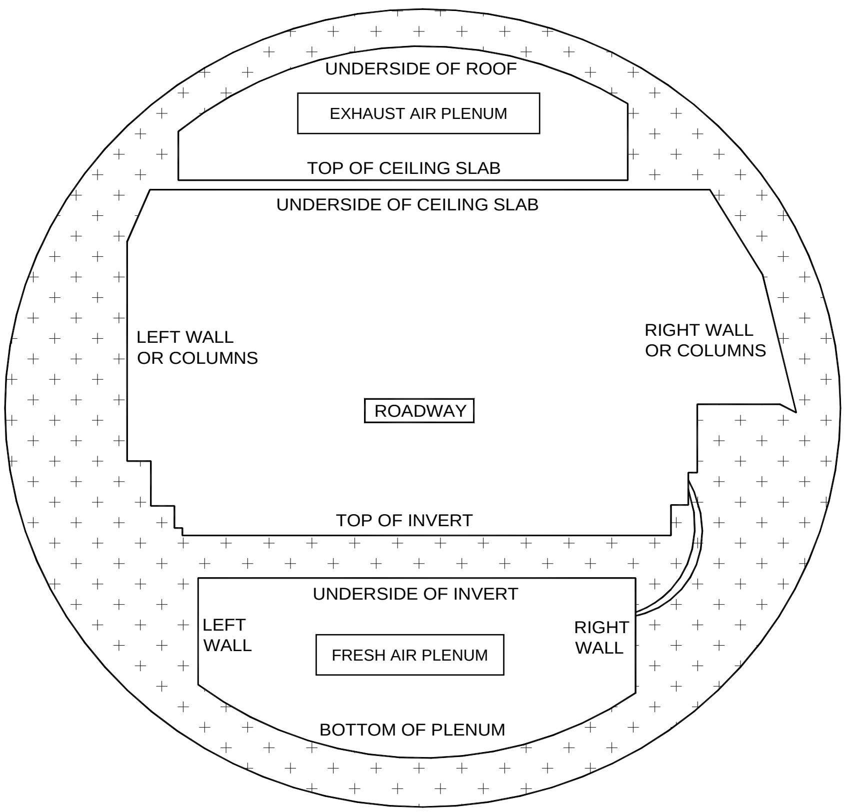

Figure 4.2 – Sample labels used with circular shaped tunnel.

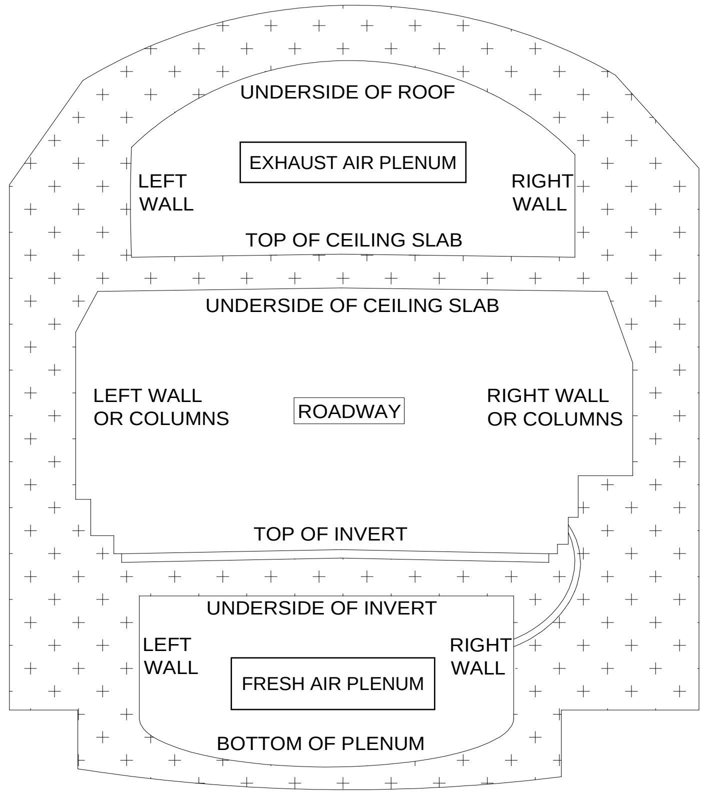

Figure 4.3 – Sample labels used with horseshoe shaped tunnel.

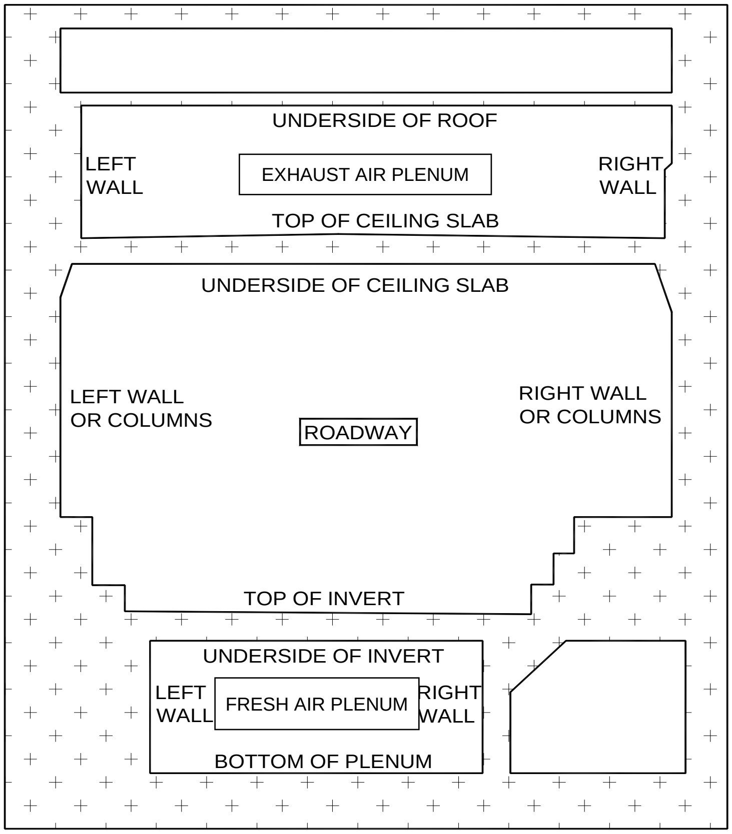

Figure 4.4 – Sample labels used with rectangular shaped tunnel.

4.6 Types of Tunnel Inspections

There are several types of inspections that are regularly performed on highway structures such as tunnels in addition to any general, daily, weekly, or monthly walk-through inspections done by the tunnel operating and maintenance personnel. Similar to other inspection programs, the NTIS identifies initial, routine, damage, in-depth, and special inspections for tunnels. Table 4.2 summarizes these types of inspections for a tunnel.

Table 4.2 – Types of highway tunnel inspections.

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

The interval requirements for initial inspection and routine inspections are contained in the NTIS, Table 4.3 summarizes these requirements. The tunnel inspection organization is responsible for establishing the inspection intervals for in-depth inspections based on the particular needs of the tunnel facility. Special and damage inspections are performed at the discretion of the tunnel owner.

4.6.1 **Initial Inspection**

An initial inspection should be performed on existing highway tunnels within the interval specified in the NTIS. On new tunnels, the initial inspection should be conducted after the completion of construction activities and the testing of functional systems but prior to opening the tunnel to traffic. See Table 4.3.

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. The results are to be recorded in accordance with the instructions contained in the SNTI.

The initial tunnel inspection establishes the baseline conditions of the tunnel; and it is used to field verify the initial tunnel inventory data. The baseline results can be used to evaluate changes over time to the tunnel systems and to help identify trends.

Table 4.3 – Interval period contained in the national tunnel inspection standards.

Activity Type	Application	Interval
Initial Inspection	New tunnel	Prior to opening to traffic to the public.
	Existing tunnel	Within 24 months of NTIS effective date.
Routine Inspection	Default condition	Every 24 months over lifetime of the 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 the program manager.

4.6.2 **Routine Inspection**

Following the initial inspection, routine inspections are conducted within the intervals specified in the NTIS. See Table 4.3. Routine inspections are regularly scheduled inspections that help to ensure continued safe, reliable, and efficient service. These inspections are similar in scope to the initial inspection. Routine tunnel inspections record the changes to the tunnel over time and can be used to help identify trends and predict future life expectancy of components.

At a minimum, routine inspections consist of a sufficient number of observations and measurements that can be used 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. The results are to be recorded in accordance with the instructions contained in the SNTI.

4.6.3 **Damage Inspection**

Damage inspections are performed in response to natural disasters or human activities that damage the tunnel. Damage may occur by motor vehicle impact, fire, flood, earthquake, vandalism or explosions. When severe damage occurs, the tunnel should remain closed until a damage inspection has been completed. Structural analysis and follow-up emergency repairs may be needed. Structural materials may need further evaluation as identified in the Manual for Bridge Evaluation (MBE).

Safety is of paramount importance after an incident. Devices such as breathing apparatus, protective clothing, and specialized equipment may be necessary. Inspection work should be coordinated with emergency responders. It is important that the tunnel inspection organization develop detailed plans and conduct training exercises with tunnel facility personnel in advance of these events.

4.6.3.1 **Impact Event**

Impact damage from motor vehicles is relatively common within a tunnel. Numerous impacts have been caused by trucks striking the tunnel or equipment attached to a trailer that was not properly secured. This type of damage usually occurs around the portal location, along the roof, and where equipment is located above the roadway. It is also not uncommon for vehicles to crash against railings, curbs, and walkways (Figure 4.5).

Figure 4.5 – Evaluating impact damage.

The following items should be inspected, as appropriate, after an impact event:

1. Tunnel lining for damage and loose tile.
2. Tunnel ceiling.
3. Tunnel lighting.
4. Steel, timber or concrete tunnel supports for damage.
5. Low hanging equipment and their anchorage system, such as jet fans, suspended ceiling system, lighting system, and detection and communication equipment.
6. Elements along the roadway such as railings, curbs, and walkways.

7. Drainage areas. In some instances, fuel can spill from crashed vehicles and flow into the tunnel drainage system and present a fire hazard at the collection points in the drainage system.

4.6.3.2 **Fire Event**

During a fire, the safety of users and responders is the first priority. The tunnel will usually require emergency ventilation measures to exhaust the smoke, vent superheated gasses, and maintain a tenable environment for the evacuees and first responders. Fuels and other combustible materials on board vehicles can increase the severity of the fire. Spilled fuel may also accumulate in collection points in the drainage system and be transported to other parts of the tunnel. Some drainage systems may discharge fluids contaminated with fuels to locations outside the tunnel. Monitors should be used to evaluate the explosive gas levels after a crash.

Figure 4.6 – Evaluating fire damage.

When evaluating damage (Figure 4.6), it is useful to estimate the intensity of the fire. This information can be used to support follow-up evaluations regarding the performance of a particular tunnel system during a fire event. One technique for estimating the highest temperature achieved is to identify objects that have melted and note any color changes in materials. These observations might provide an indication about the maximum temperatures experienced. Melting points for common materials include plastic at 300 – 450 ºF, lead at 620 ºF, glass at 750 – 900 ºF, and aluminum at 1,200 ºF.

Timber – Fire damage is easily evaluated on most timber structures. Fire damage may not be as severe as first expected. The best way to determine the extent of damage is to chip away at the charred remains of the timber at several locations and then measure the remaining section of the unblemished timber. The greatest section loss is often located where two or more members are fastened together.

Concrete – Concrete and masonry usually perform well during fire events; but when temperatures exceed about 570 ºF, permanent damage may result. As the temperature rise, the concrete may experience discolorations that progresses from pink to white to a grey-buff at very high temperatures. The discolorations (Figure 4.7) should be noted in the inspection findings.

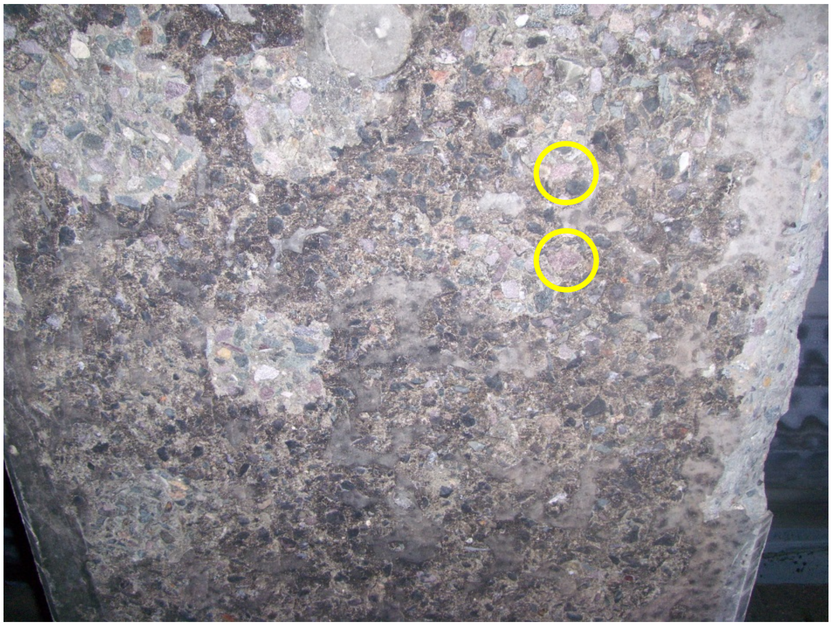

Figure 4.7 – Color change can indicate the highest temperature experienced.

A hammer should be used to sound areas of concrete that have been exposed to fire; the concrete should be checked for delamination or damage such as cracking, distortion, spalling, or any other indications of damage. Reinforcement that is exposed should be identified.

Steel – Steel subjected to fire should be carefully examined for evidence of deformation since it tends to lose stiffness at higher temperatures. The straightness of the members should also be checked; and the amount and location of damage should be measured and documented. Members exposed to extreme heat may experience excessive deformations and permanent strength reductions. Steel subjected to fire can be sampled using coupons. The mechanical properties can be tested for brittleness or hardness. Appropriate non-destructive testing may also be beneficial.

It is important to check that the steel connections are not damaged. Look for sheared bolts, loosened rivets, or other damages caused by excessive thermal stress/strain. Welds can be cracked or torn.

4.6.3.3 **Flood Event**

After a flood, the embankments and slopes around the tunnel may become saturated with water. This condition may lead to instability of walls and slopes. A geotechnical engineer should investigate the embankments and slopes in the vicinity of the tunnel after a flood event. Excess water should be pumped from the tunnel, and debris should be removed. Check areas that are difficult to access, such as ventilation ducts, equipment rooms, and emergency corridors for standing water and debris. The potential for electric shock needs to be evaluated by a qualified person prior to restoring power to the tunnel.

After the tunnel is rendered safe, the inspectors should evaluate the effectiveness of the flood gates, if applicable, and document the extent of water damage. Functional systems that have been exposed to flood waters should be checked for damage. Electrical systems can be ruined by floodwaters, especially when saltwater is involved. Check the essential equipment to ensure functionality can be restored. After a flood event, the tunnel may need to be thoroughly washed, particularly in saltwater environments.

4.6.3.4 **Seismic Event**

Tunnels are resilient to seismic shaking; however, large ground movements from a seismic event may still result in extensive damage to major components. The greatest risk of severe damage for a tunnel facility occurs from:

- An active fault intersecting the tunnel;
- A landslide intersecting the tunnel; or
- Liquefiable soils..

It is good practice to have an inspection plan ready for immediate implementation in areas with seismic activity. Following an earthquake of 5.0 or more on the Richter scale, all tunnels within 100 miles of the epicenter should be inspected. The inspection team should use caution following and earthquake since aftershocks may follow; and when the tunnel is located in a low lying coastal area, it could be at risk for a tsunami. After the danger has cleared, inspect for:

1. Cracks, slides, or slope failures in embankments near the tunnel portals.
2. Rock falls and loose rock.
3. Tilt in walls adjacent to the tunnel portals.
4. Fallen or loose material such as tiles that may fall.
5. New cracks or failures in the tunnel lining or road surface.
6. All suspended items and overhead attachments to the tunnel such as suspended ceiling, jet fans, lighting system, and signs, Check for sound anchorages.
7. Offsets due to displacement across a fault.
8. Steel, timber, masonry, or concrete structure elements for damage.
9. Increased or unusual flow of water within the tunnel, especially if tunnel is submerged.
10. Functional systems, such as drainage, ventilation and lighting, communication equipment, and safety systems should be inspected as a general precautionary measure. When flooding occurs because of tsunamis, follow the flood event procedures.

4.6.3.5 **Blast Event**

Blast events can cause widespread or local damage, and this damage can be hard to predict. Experts in urban search and rescue, structural engineers, security, and law enforcement experts will likely be required to be at the scene to ensure safety and evaluate the damage. The tunnel site may be treated as crime scene, and access to the site may be limited by the authority in charge. Before conducting a damage inspection, inspectors should be aware of issues associated with a blast event such as poor air quality, the possibility of hazardous materials, and the potential for spilled fuels and other combustible or dangerous materials.

When damage occurs from a blast event, the impact, fire, and seismic damage procedures should be followed as appropriate. In addition, all potentially impacted windows and doors should be inspected for damage from the shockwave. The tunnel inspection organization, the tunnel facility personnel, and first responders should have procedures in place to deal with blast events as appropriate for the tunnel facility.

4.6.4 **In-Depth Inspection**

In-depth inspections are close-up, hand-on inspections conducted on one, several, or all of the elements or functional systems. These inspections are used to identify deficiencies that are not readily detectable during initial, routine, or damage inspections. In-depth inspections may involve testing of tunnel system, components, and materials. More extensive disassembly and cleaning of equipment parts may occur. This type of inspection may be used to support a structural analysis or a functional system evaluation where more information is needed. In-depth inspections are scheduled based on the needs of the tunnel facility, inspection findings, and established written procedures.

4.6.5 **Special Inspection**

A special inspection is typically performed after an initial, routine, damage or in-depth inspection when significant deficiencies have been discovered and need to be monitored. Special inspections are scheduled based on the needs of the tunnel facility, inspection findings, and established written procedures. These types of inspections continue, but perhaps at adjusted intervals or durations, until the deficiency is repaired, the component is removed from service, or further study determines that the conditions are no longer deteriorating at accelerated levels. For example, a light fixture built of dissimilar metals and installed over traffic might have problems with excessive corrosion. As such, this light fixture may be monitored on a regular basis to ensure that it remains securely anchored and safe until repairs can be made.

4.7 Health and Safety Considerations

Tunnel inspection must be conducted in a safe manner. Rescue in tunnel facilities can be complicated because tunnels have limited access points and areas of confined space. Some of the dangers in tunnels include energized equipment, highway traffic, service and emergency vehicles, power supply, rigid objects, sharp edges, working from heights, flying debris, and hazardous materials.

The activities of the inspection team should be closely coordinated with the personnel at the tunnel facility. The traveling public should also be protected from any hazards of the inspection work. Written health and safety procedures should focus on preventing injury, death, and equipment damage to ensure the overall success of the inspection program. The goal should be to complete the inspection with zero accidents.

4.7.1 **Key Concerns for Tunnel Inspection Safety**

Health and safety plans must address the dangers inherent to the inspection process. The proper attitude, alertness, and common sense are important components of safety. Everyone should be engaged in safety. A competent person should be on-site to identify workplace hazards relating to specific operations, who has the authority to correct any deficiencies [29 CFR 1926.32(f)].

Figure 4.8 – Typical safety placard. This photo shows a sign labeled, "WEAR YOUR VEST," and a notebook containing material safety sheets is hung to the wall for use of inspectors and other tunnel workers.

Inspections of overhead items usually require one or more lane closures and fall protection for the workers. It may be necessary to close the tunnel bore when performing inspections to lessen the risk of accidents. Personal protective equipment is required (Figure 4.8). Applicable laws and regulations should be followed. Written safety procedures need to be developed and implemented. Inspecting plenums and equipment rooms might involve confined space entry procedures to meet Occupational Safety and Health Administration (OSHA) rules.

Some basic safety issues that may arise in inspections are: injury and pain, family hardship, equipment damage, lost production, and medical expenses.

- Injury and pain - Accidents can cause pain, suffering, and even death. Carelessness is often a contributor to jobsite accidents.

- Family hardship - A worker's family may also suffer hardship from an accident. There can be loss of income; the injured person may not be able to participate in family activities; and in the case of a major disability, the burden of caring for the injured person may be borne by family members.

- Equipment damage - Equipment can be very costly to repair. The damage to equipment must be fixed and, depending on the severity of the damage, there may be a lost time if the equipment is not available for use.

- Lost production - The employer loses revenue when the employee is not able to complete the job assignments. Time and money may also be lost retraining a new employee and resupplying the job with equipment that works. Additional training may be needed for the crew to prevent further injuries.

- Medical expenses – Incurred medical expenses impact the tunnel owner, the employer, and the insurance company in most cases.

4.7.2 **Safe Working Environment**

A safe working environment is essential for preventing injury and damage. The health and safety plan should focus on establishing a safe working environment that is facilitated by:

- Establishing written safety procedures that are clear, effective, and thorough.
- Providing adequate levels of safety training.
- Using tools and equipment properly.
- Implementing job site safety plans.
- Ensuring that work is properly supervised.
- Addressing safety incidents.
- Identifying safety incidents and relevant case studies.
- Instructing equipment operators.
- Enforcing safety regulations.
- Requiring emergency action plans that include emergency responders.
- Providing contact information for emergency responders and essential personnel.

Tunnel inspectors should take responsibility for their own safety and that of their co-workers. The following are useful actions for personal safety:

- Recognizing their own physical limitations – Inspection team members must notify the appropriate person, such as the team leader, when they don't feel capable of performing an assigned task. Other team members may not realize the limits of others. An individual, who feels unqualified or uncomfortable performing a particular task, should speak-up and discuss their assignment with their supervisor to prevent putting themselves or others at risk.

- Understand the rules and requirements of the job – If an individual doesn't understand how the work is to be performed, then this person should ask questions to clarify the situation, particularly when a task seems unsafe. When this occurs, the process should be reviewed and discussed to the satisfaction of all those involved, any misunderstandings should be clarified, and a safer alternative procedure developed. The inspection work should not proceed until all safety concerns have been satisfactorily resolved.

- Protecting coworkers – Team members must not endanger the health and safety of coworkers. When unsafe acts are observed, the person committing the unsafe act should be warned and team leaders should take appropriate action to discourage and prevent any reoccurrence.

- Reporting an accident - An accident must be reported to the person designated, such as the team leader or program manager. An injury should be promptly reported in accordance with established written procedures. These actions will promote proper resolution of accident and comply with insurance claim requirements.

    - If possible, a concise journal of events should be kept by anyone who witnesses or is involved in an incident. As soon as possible, observations should be recorded and pertinent information should be jotted down such as the time and date of the incident. It is good practice to also keep track of the name and title of the persons that were notified about the incident including the time, date, and method of reporting the incident, such as telephone, e-mail, or verbally. If any directions or responses were provided, it is advisable to summarize these into the journal as well.

    - It is also important to report near-misses that may help prevent similar incidents that could be worse.

4.7.3 **Personal Safety**

Personal safety measures are aimed at providing protection and minimizing risks to members of the inspection team. Some of the ways in which team members can be made safer on the job include the proper inspection attire, appropriate safety equipment, accident awareness, and enforced safety rules. It is important that the appropriate safeguards are put into practice and that the safety concerns of the job are clearly communicated and understood.

Inspection Attire – The proper inspection attire should be worn for the job and be representative of the hazards for the work. Field clothes should be sized for the individual and they should be appropriate for the weather and site conditions. Work clothes should generally fit snug and be comfortable.

The arms, legs, and torso should be protected by sturdy work clothes. The hands and feet should be protected by suitable gloves and boots. For general inspection activities, the inspector should wear leather boots with traction lug soles (non-penetrable soles). For climbing, the inspector is encouraged to wear boots with a steel shank (with non-slip soles without heavy lugs) or boots as per agency policy. Leather gloves that allow the inspector to pick up tools and write notes are recommended. A tool pouch enables the hands of the inspector to be free for climbing and other inspection related tasks such as taking notes and performing tests.

Personal Safety Equipment – Safety equipment or personal protective equipment (PPE) is designed to reduce the occurrences of injury and death. The head is normally protected using hard hat, goggles, ear plugs, and dust mask or respirator as necessary. Harnesses with lanyards offer fall protection when working at heights. Vests provide increased visibility to traffic. Much of this equipment needs to be fitted to the individual. Safety training for using PPE should be provided by a qualified safety representative.

Hard Hat: Serious head injuries may be reduced by wearing a hard hat; it is recommended that everyone in the field wear a hard hat at all times. When moving about in the tunnel, a hard hat provides an increased level of head protection against falling objects and accidental impacts with rigid or sharp objects. Objects to be careful around include:

- Deteriorated tunnel components that can be dislodged during the inspection process.
- Equipment dropped from overhead.
- Airborne debris from passing traffic.

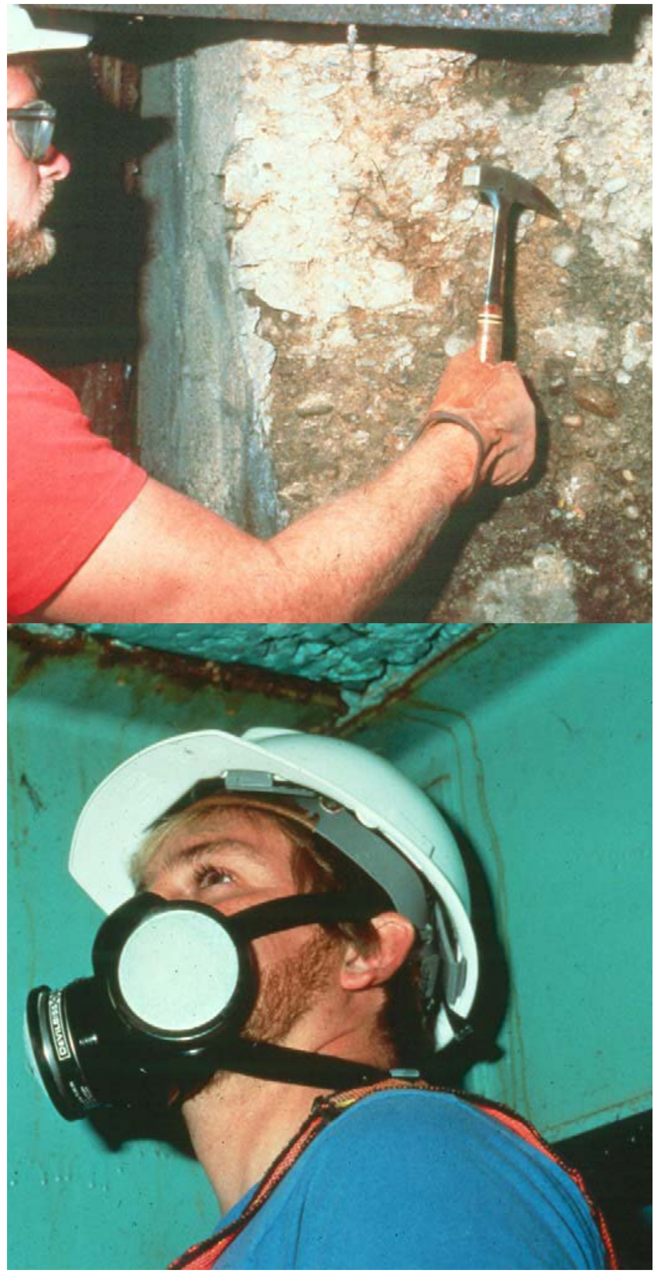

Figure 4.9 – Personal protective equipment: top, eye protection; bottom, respirator.

When climbing in the tunnel or using lift equipment, inspectors frequently come close to rigid objects such as utility brackets and structural components. Many of these elements also have sharp-edges. Wearing a hard hat at all times while working can prevent serious injury or even death.

Reflective Safety Vest: When performing activities near traffic, the inspector should wear an appropriate safety vest. It is good practice to wear the safety vest at all times while conducting the work. The vest should be brightly colored with reflective strips that conform to the latest American National Standards Institute (ANSI) requirements for the type of traffic at the site. The combination of bright colors and reflectivity of light allows fellow workers, equipment operators, and passing motorists, to quickly identify the person and avoid injury. Some tunnel facilities have their own safety vest requirements, and it is best to verify these prior to showing-up in the field.

Safety Goggles: Eye protection is necessary to prevent damage to the eyes from flying particles and debris, see Figure 4.9, top. Glasses with shatterproof lenses should be supplemented with adequate side protection; or the glasses should be covered by safety goggles. Eye protection should usually be worn at all times, but is necessary when:

- Using a hammer or mallet.
- Using a scraper or wire brush.
- Grinding, chipping, cutting, sawing, or drilling.
- Working near moving machinery or equipment.
- Working in ventilation shafts or chambers where the air picks-up debris.
- Working in areas adjacent to traffic where debris is kicked-up by passing vehicles.

Dust Mask / Respirator: A respirator or dust mask can protect the inspector from harmful airborne dust, contaminants, and pollutants, see Figure 4.9, bottom. OSHA and other appropriate requirements should be followed when wearing these devices. Conditions that usually require a respirator include:

- Sandblasting.
- Painting or removing paint.
- Exposure to pigeon droppings (to prevent serious infections such as Histoplasmosis).
- Working in confined areas, around hazardous materials or dusty conditions.
- Cleaning items with compressed air.

Safety Harness and Lanyard: Safety harnesses and lanyards provide protection from falls by tying off the individual to rigid objects. To reduce the potential for back injury, a shock absorber should be incorporated into the lanyard. This shock absorber reduces the g-forces by controlling the rate of extension during a fall and typically uses nylon webbing, pre-folded and sewn together. Prior to wearing the device, the safety harness and lanyard should be thoroughly inspected and fitted to the individual. Any device that is fretted, worn, or expired should not be worn. If a lanyard is deployed in a fall or if it has reached its expiration date, the lanyard must not be used.

The safety harness must be tied-off securely to a solid structural member or a safety line rigged for this purpose. Scaffolding can fail and bring down whoever is tied to it. When working from a man-lift or a lift-bucket, the appropriate cautionary measures should be implemented to prevent injury. For example, if someone is tied off to a stationary object such as the tunnel liner, and the lift basket is moved beyond the length of their lanyard, the individual in the basket may be injured by the maneuver or pulled from the basket. A trained and certified person should always be assigned to evaluate the job-site conditions prior to tying off with lanyards.

Gloves: Gloves protect the hands and, to some degree, the forearms against objects that are rough, sharp, hot, or otherwise harmful. Deteriorated structural members typically have sharp edges and rough surfaces that can easily cut hands and arms, and injuries such as these can be quite painful and can become infected. If an artery is severed, significant blood loss may occur requiring emergency measures.

4.7.4 Accident Prevention

Accidents are often caused by human error from carelessness, improper attitude, or taking shortcuts. The risks to workers are minimized by planning ahead, implementing safety awareness campaigns, and maintaining inspection equipment in proper working order.

Preventable Accidents – Contributing factors to preventable accidents include:

- Improper attitude - distraction, carelessness, or worries over personal matters.
- Personal limitations - lack of knowledge or skill or exceeding physical capabilities.
- Physical impairment - previous injury, illness, side effect of medication, alcohol or drugs.
- Boredom - falling into an inattentive state while performing repetitive or routine tasks.
- Thoughtlessness - lack of safety awareness and not recognizing hazards.
- Shortcuts - sacrificing safety for time.
- Faulty equipment – worn tools, damaged ladder rungs, or frayed cables.
- Failure to use or maintain personal protective equipment.
- Lack of appropriate clothing to protect exposed parts of the body or inappropriate clothing that puts the individual at greater risk.

Safety procedures should minimize the occurrence of safety incidents. Supervision, breaks, check-lists, and drills have been used successfully to focus attention on safety.

Common Sense Safety Precautions – Some common sense safety precautions are listed and briefly discussed below:

- Keep well-rested and alert – The working conditions encountered during an inspection can change; the inspector should be aware of these changes and respond accordingly. The work may become tedious at times and a drowsy inspector is at greater risk for accidents.

- Maintain proper mental and physical condition – Inspection tasks require a number of different motor skills to maintain adequate safety. To perform at acceptable levels, the inspector should be physically fit, free from mental distractions, and focused on the job.

- Use proper tools – Do not use tools and equipment that are not suitable for the work. Make sure the tools are in good working order. Do not use broken or worn tools.

- Keep the work area neat and uncluttered – Tools and equipment scattered about the work area present a safety hazard and demonstrate a general lack of safety awareness.

- Establish systematic procedures – Procedures should be established early in the job and then implemented thoroughly throughout. Procedures should be clear and concise so that everyone knows what to expect and there are no surprises.

- Use lockout/tagged-out procedures – Follow lockout/tag-out procedures when inspecting energized or potentially energized systems. Energized equipment can be dangerous when not treated with proper care and attention. Persons working with energized equipment should be knowledgeable and certified to perform the work.

- Follow safety rules and regulations – Adhere to the safety rules and any appropriate laws and regulations. Audits and checks should be instituted to ensure compliance.
- Use common sense and good judgment – Do not engage in horseplay, and do not take short cuts or foolish chances. Team leaders should take responsibility to enforce procedures to ensure a safe environment.

- Avoid the use of intoxicants or drugs – Intoxicants impair judgment, reflexes, alertness, and coordination. Team members may be subject to drug and alcohol screening or after-accident testing. A policy of zero-tolerance is common for these types of offenses.

- Medication – Prescription and over-the-counter medications can cause drowsiness or other unwanted and potentially dangerous side effects. The inspector should always discuss the medication with the prescribing doctor. It’s good practice to carry the prescription and to discuss any potential side effects with the appropriate persons such as the team leader or job-site medic.

- Electricity – Electric currents are very dangerous. It is commonly believed that as little as one amp of electricity can produce fatal heart irregularities in a person. All cables and wires should be assumed to be hot (live) until properly tested and lockout/tagged-out.

    - Even if wires and cables appear to be low-voltage, control, networking, or telephone cables, serious injury or death can result.
    - Tunnels contain many shock hazards such as through steel members, water leaks, humidity in the air, and water sprays.
    - If there are any transmission lines within the tunnel, they should be identified prior to the inspection.

- Buddy system – Inspectors should work in pairs. There should always be someone who can react to an accident. Inspectors should communicate their position with others, and the team leader should know where everyone is working. If anyone appears to be missing or out of place, efforts should be made to locate that person immediately.

- Overhead items – It is best to avoid working above traffic and people. If it cannot be avoided, the inspection crew working overhead should use safety lanyards to secure tools and notebooks from falling onto persons or vehicles below.
- Dark areas – Use a flashlight to illuminate dark areas prior to entering them. It’s easy to become injured when entering a dimly lit room due to trips, falls, sharp objects, rigid or unprotected components, and exposed cables. Furthermore, pests such as snakes, insects, spiders, mice, and rats can bite, sting, poison, or startle the inspector.

4.7.5 **Hazardous Materials**

Asbestos and lead can be found in many older tunnels. Other hazardous materials may also be present. When hazardous materials are suspected at an inspection site, the issues should be thoroughly investigated, necessary precautions taken, and applicable laws and regulations should be followed. *It is advisable to consult with an appropriately qualified health and safety or environmental specialist, who is knowledgeable of applicable laws and regulations, to plan out the work.* Hazardous materials can pose health and safety risks, and environmental laws often control proper actions with work around them.

Asbestos – Asbestos-containing materials (ACM) are present in many tunnels that were constructed before 1980. Newer tunnels typically do not contain asbestos materials. An environmental health and safety specialist should be consulted to help plan out the work around ACMs of any type. Material testing and remediation operations for asbestos are conducted in accordance with the EPA 40 CFR 61, Subpart M.

ACMs are typically categorized as either "friable" or "non-friable". Friable ACMs are the materials that, when dry, are readily crumbled, pulverized, or reduced to a powder by simple hand pressure. Examples of friable ACMs include: pipe insulation, caulk, ceiling tile, wallboard, building insulation, thermal system insulation, and sprayed-on fireproofing. Non-friable ACMs include the materials that cannot be crumbled, pulverized, or reduced to powder by simple hand pressure. Non-friable materials usually contain a binder that combines the asbestos fibers into a matrix. Examples of non-friable ACMs include: vinyl floor tiles, floor tile mastic, most roofing materials, adhesives, cement flue patching, asphalt pavements, expansion joint material, mastic coatings, and cementitious pipes. Most non-friable ACMs can become friable by mechanical operations such as sanding, grinding, drilling, or abrading.

Materials that contain friable or potentially friable ACMs should be avoided. When these materials are suspected or observed during the course of an inspection, they should be noted in the inspection documents and reported to the tunnel owner. It is important that asbestos fibers do not become disturbed or airborne since these fine fibers or dust can be inhaled and, over prolonged periods. The asbestos fibers can cause serious and even fatal illnesses such as lung cancer, mesothelioma, and asbestosis.

Lead – Based on the age of the tunnel, the potential exists for chemical contaminants, particularly lead, to be present in the settled dust of the tunnel plenum. Vehicles emitted lead in their exhaust prior to the 1980s when gasoline contained this additive to boost the octane rating. Many tunnels have since been cleaned of lead. If lead is suspected in a tunnel constructed prior to 1990, or if there is no record of the tunnel being cleaned of lead, then it is advisable to consult with an appropriately qualified health and safety or environmental specialist to help plan out the remediation.

OSHA regulations governing lead exposure should be understood. The General Industry lead standard is contained in 29 CFR 1910.1025. The Construction Industry lead standard is found in 29 CFR 1926.62. The OSHA Permissible Exposure Limit (PEL) is 50 ug/m^3 (micrograms per cubic meter of air), which is averaged over an 8-hour workday. The OSHA action level (AL) exposure limit to lead is 30 ug/m^3. Exposures greater than the AL require lead monitoring for impacted workers.

Site specific work plans should be developed to protect workers from overexposure to lead during the inspections. The following methods and procedures may be explored in further detail to potentially reduce exposure levels:

- Conduct an initial exposure determination according to 29 CFR 1910.1025(d)(6)(i). This consists of conducting personal exposure air monitoring for lead. The analytical and sampling methods are found in the National Institute for Occupational Safety and Health (NIOSH) Method 7300 or OSHA ID 121 or 125G; **or**

- Dust samples can be collected or x-ray fluorescence direct-reading methods can be employed to determine the content of lead in dust. The material should be wipe sampled and analyzed as determined by ASTM E1728, “Standard Practice for Field Collection of Settled Dust Samples Using Wipe Sampling Methods for Lead Determination by Atomic Spectrometry Techniques”, or equivalent method, with an acceptable wipe material as defined in ASTEM E1792, “Standard Specification for Wipe Sampling Materials for Lead in Surface Dust.” Note: There is no current minimum amount or concentration of lead to trigger a determination of lead and the potential for occupational exposure. However, if the employer has appropriately tested all potential sources for lead (e.g., tested all layers of paints and coatings that may be disturbed) utilizing a valid lead test detection method and found no detectable levels of lead, the standard does not apply.

- If lead is found to be present in the dust, personal protective equipment, including respiratory protection should be issued to personnel in accordance with OSHA 29 CFR 1910.134 or 1926.103. In the absence of an initial exposure determination, minimum personal protective equipment should include air-purifying respirators equipped with P-100 filters and disposable Tyvek™ suits.

- Workers should also be instructed on good personal hygiene practices, including washing hands before eating and showering before leaving the worksite.

4.7.6 **Lockout/Tag-out**

Lockout/tag-out procedures should be developed during inspection planning. Prior to inspecting any mechanical or electrical equipment with the potential to cause injury or damage the lockout/tag-out procedures should be implemented in coordination with the appropriate tunnel facility personnel. The inspection should not be allowed to proceed until the system is properly de-energized or isolated, locked-out, and tagged out. Figure 4.10 shows a sample lock and tag that may be used as part of this procedure.

Unexpected energized circuits or startup of machinery and equipment, or the release of hazardous energy during service or maintenance activities can sometimes occur after lock-out/tag-out. Therefore, it is important to create a checklist to ensure that safety is maintained. The following procedure can be used as a guide to help develop a lockout/tag-out procedure for machinery and equipment:

Figure 4.10 – Typical lock and tag-out system.

Machines or equipment should be stopped, isolated from all energy sources, and locked out. Employees should not be allowed to congregate near the equipment being removed from service in case of unexpected energizing or the accidental start-up of the machine.

Sequence of Lockout

(1) The shutdown should be coordinated with the appropriate personnel at the tunnel facility. Even if the equipment isn't running at the moment, it may be possible to turn on the equipment at the flick of a switch in another room or by some algorithm written into a computer program. Always use established procedures and qualified personnel for the shutdown.

(2) The person conducting the shutdown should follow the appropriate procedures. The type and magnitude of energy running to the equipment should be identified. The person initiating the shutdown should be competent and appropriately qualified for servicing the particular equipment. The qualifications of this individual should be listed in the written procedures. This person needs to understand how to isolate and control the energy running to the equipment.

(3) Notify all persons (e.g.,, employees, maintenance staff, on-site contractors) working in the vicinity of the equipment being shutdown, as appropriate and in accordance with established procedures. Inform these people that servicing has been scheduled for the equipment and that the machine will be removed from service.

(4) De-activate all sources of energy to the machine and isolate the equipment from all energy sources.

(5) Lockout the energy using isolating devices and provide locks assigned to individuals that prevent these isolating devices from being removed. Use appropriate blocking and shields as necessary to secure the equipment. Add tag designations to the equipment. The locks and tags should contain the appropriate identification and contact information of the person responsible for the shutdown.

(6) Stored or residual energy—from capacitors, springs, elevated machine members, rotating flywheels, hydraulic systems, and air, gas, steam or water pressure—should be dissipated or restrained by appropriate methods such as grounding, repositioning, blocking, or bleeding down. These techniques should be covered in the written procedures.

(7) Perform checks as necessary to ensure that the equipment is properly isolated. One method of checking is to attempt to switch on the equipment. *When attempting to turn back on the equipment, clear everyone to a safe distance, clean up tools and loose parts, and ensure that feeder lines are properly secured. If the lockout/tag-out procedure was inadequate for any reason, it's possible that the equipment will reenergize and endanger the occupants in the room.* By using the normal operating controls, the feeder lines can be tested for energy; and the machine can be observed for signs of power. If the machine turns-on, lights-up, or has moving gauges, then power is likely getting to the equipment and the cause should be further investigated. Successful implementation of this check should increase the level of confidence in the lock-out procedure; and it serves to validate the process. Once this check has been completed, the operating controls should be switched back to the neutral or "off" position.

(8) The equipment should now be effectively locked-out.

Restoring the Equipment to Service

When reenergizing equipment or machines after a shutdown, it is important to follow a carefully controlled process to prevent injury or equipment damage. When the servicing is complete and the machine is ready to be returned to service, the following steps should be considered when instructions are not already available:

(1) Check the equipment and the immediate area to ensure that nonessential items have been removed from the area and that the machine components are operationally intact.

(2) Check the work area to ensure that all employees have been safely positioned or removed from the area.

(3) Verify that the controls are in neutral or “off”.

(4) Remove the lockout devices and tags.

(5) Provide any visual or audible safety warnings deemed necessary prior to re-energizing the equipment.

Note: The removal of some forms of blocking may be necessary prior to re-energizing the machine.

(6) Notify affected employees that the servicing, maintenance, or inspection has been completed and that the machine or equipment has been placed back into service.

4.7.7 Confined Space Entry

Tunnel inspections often include team members entering areas of confined space. Confined space is distinguished by the need to obtain a permit for entry, which is regulated by OSHA. Confined space is large enough for human entry with limited means of egress and not designed for continuous occupancy. Permit-required confined space usually poses a hazard or danger to the occupants. *When planning inspection in a confined space, it is advisable to consult with an appropriately qualified health and safety specialist, who is knowledgeable of applicable laws and regulations.*

There are five major concerns when performing inspections within confined space:

- Lack of oxygen – oxygen content should be maintained within certain limits to ensure the health of the inspectors and to lessen the chance for any explosions.
- Toxic gases – produced by tasks such as painting, burning, welding or operation of internal combustion engines.
- Explosive gases – natural gas, methane, or gasoline vapors may be present.
- Lack of light – many confined spaces are nearly totally dark. Inspectors need to be able to spot potential hazards and dangerous conditions. Adequate light is also necessary to perform the inspection
- Limited means of access – many confined spaces have limited points of access and therefore limited locations for emergency egress.

Figure 4.11 – Air testing and monitoring.

Proper ventilation, additional lighting, and effective communication procedures can help mitigate many of the hazards of confined space; however, some areas of confined space also require permits to enter along with specialized training to meet OSHA requirements.

Safety Procedures for Confined Space – OSHA publishes regulations that govern confined space entry, and these requirements must be followed. When operating in confined space, the proper training, equipment, and permitting are necessary. Equipment such as respirators, tie-off ropes, two-way radios, and meters to measure the gas levels may be required. It is important to monitor gas levels in areas of known ground contamination or where potentially dangerous materials are encountered.

The following safety procedures should be considered when inspecting areas that are characterized as confined space.

Pre-entry air tests (Figure 4.11):

- Test for oxygen with an approved oxygen testing device.

- Test for other gases, such as carbon monoxide, hydrogen sulfide, methane, natural gas, and combustible vapors.

Mechanical ventilation:

- Pre-entry – Oxygen and gas levels should be acceptable for a minimum prescribed time prior to entry.
- During occupancy – Ventilation should be continuous regardless of activities. Test for oxygen and other gases at prescribed intervals during occupancy.

Basic safety procedures:

- Avoid the use of flammable liquids in the confined area.
- Position inspection vehicles away from the entrance areas; and avoid creating carbon monoxide fumes.
- Position generators "down-wind" of operations.
- Operations that involve the production of harmful gases or dust should be performed "down-wind" of personnel.
- Carry an approved rescue air-breathing apparatus (Figure 4.12) as appropriate.
- Use adequate lighting with an appropriate backup system. Lifelines should be considered when entering areas that could become dangerous when dark.
- Inspection should be performed in teams, with a person remaining outside of the dark area or area of confined space. This person should be able to communicate with others if any serious problems develop.
- Use communication devices such as two-way radios or cell phones for general and emergency contact; however, make sure that any devices used are reliable in the areas where the work is being performed. Cellular phones may not work in all parts of the tunnel.
- Be familiar with the confined space entry plan and emergency or rescue procedures.

Figure 4.12 – Rescue air-breathing apparatus.

4.7.8 **Public Safety**

The requirements from the *Manual on Uniform Traffic Control Devices (MUTCD)* should be followed on how to position traffic control devices; this document is published by the Federal Highway Administration (FHWA). It is also available from the Institute of Transportation Engineers (ITE) and the American Association of State Highway and Transportation Officials (AASHTO).

All appropriate State, Federal Land, and Tribal government laws, regulations, and policies should also be followed. Coordination and advance planning is essential. Some jurisdictions may require that state or local police be on-site during the inspection to improve the safety of the inspection team and the travelling public. Suitable warning and protective devices are needed to alert the public of any potential hazards and dangers.

4.8 Inspection Equipment for Tunnels

Inspection tools are an important component of the inspection program. Equipment and tools that are commonly used for tunnel inspections are listed below:

- Aerial Bucket Truck or High Lift - Used to lift the inspector to areas inaccessible by foot or ladders and to provide close-up inspections.
- Awl/Boring Tool - Used to determine extent of deterioration in timber.
- Calipers - Used to measure steel plate thicknesses.
- Camera (35mm or digital) with Flash - Used to take photographs for documentation of the inspection.
- Chalk, Kiel, or Markers - Used to make reference marks on tunnel surfaces.
- Chipping Hammer - Used to sound concrete.
- Clipboard - Used to take notes and fill out paper forms during the inspection.
- Crack Comparator Gauge - Used to measure crack widths in fractions of an inch or millimeters.
- Dye Penetrant or Magnetic Particle Test Kits – Used to detect surface cracks in steel.
- D–Meter - Used to measure the thickness of steel.
- Extension Cord - Used to get electricity to inspection area. Surge protectors are advised.
- Field Forms - Used to document the findings, take notes, and draw sketches for the various structures.
- Flashlights - Used in dark areas to help illuminate objects during inspection.
- Portable Generator - Used when necessary to provide electricity for the inspection (lighting).
- Ladders - Used in lieu of a lifting system to access overhead areas not visible from the ground and to perform close-up inspections.
- Handheld infrared thermometer.
- Light Meter - Used to measure the brightness in the tunnel.
- Portable Lights - Used where tunnel lighting is inadequate during inspection.
- Pencil – Used to take notes and complete field forms.
- Plumb Bob - Used to check verticality of columns and wall faces.
- Pocket Knife - Used to examine loose material and other items.
- Sample Bottles - Used to obtain liquid samples.
- Scraper - Used to determine extent of corrosion and concrete deterioration.
- Screwdriver - Used to probe weep holes to check for clogs.
- Wire Brush, Paint Brush or Brooms - Used to clean debris from surfaces to be inspected.
- Tablet Personal Computer - Used to take notes or draw sketches in lieu of paper forms.
- Tape measures.
    - Pocket Tapes and Folding Rules - Used to measure dimensions of defects.
    - 100 ft. (30 m) Tape (Non Metallic) - Used to measure anything beyond the reach of pocket tapes and folding rules.

Safety equipment that meets appropriate industry standards should be furnished for the inspection team as follows:

- Appropriate devices for traffic control.
- First aid kit.
- Flashlights.
- Hardhats.
- Leather work gloves.
- Safety vests.
- Protective eyewear.
- Knee pads.
- Safety belts or harnesses.
- Work boots.
- Two-way radios appropriate for use in the tunnel. Cellular phones may be used as appropriate; however, these devices may not work in all areas of the tunnel. Only use devices that are fully functional in all areas to be inspected.
- Protective breathing masks if soot and dirt buildup is prevalent on the tunnel surfaces
- Air quality monitoring equipment.

4.8.1 **Access Equipment**

Access equipment includes man-lifts, bucket trucks, ladders, and/or removable scaffolding. This equipment is generally needed for close-up visual inspection of overhead items. This equipment allows the inspector to view the overhead structural elements and components of functional systems in a close-up, hands-on manner. In rare instances, binoculars may be used to locate surface defects on distant items, but this technique has many drawbacks and should be used on a limited basis.

4.8.2 **Non-Destructive Testing**

Non-destructive testing (NDT) methods may be used in areas that are difficult to access or in areas that require in-depth evaluations. NDT technology can also be used to characterize the extent of deficiencies in structural elements, and baseline readings from NDT technologies can be used to monitor defects over time. NDT methods are considered effective for evaluating:

- Water leakage.
- Delaminations and spalling of concrete liners due to reinforcing steel corrosion.
- Voids behind and within tunnel linings.
- Concrete permeability.
- Tiles separating from the tunnel liner.
- Detecting integrity of steel liners underneath concrete linings.
- Problems with integrity of ceiling systems and connections to the tunnel lining.

The techniques produce reasonable results when the surface area of the defects is at least 1 square foot and located at depths less than 4 inches below the surface. In some instances, these techniques are effective at deeper depths. NDT technologies are known to provide useful information; however, the limitations should be considered prior to use. Some common NDT technologies are:

- Air-coupled GPR
- Infrared thermography
- Scanners
- Ground-coupled GPR
- Ultrasonic tomography
- Ultrasonic echo
- Ultrasonic surface waves
- Impact echo

More information on NDT technology can be found at:

http://www.ndtoolbox.org/content/tunnels

There are various imaging techniques that can be used to verify the tunnel geometry and identify changes that occur with the tunnel surface over time. Also, infrared imagery is useful for identifying water leaks in the liner and component wear in motors or equipment. Water is relatively cool whereas worn parts on motors are usually hot, and infrared imagery can detect these temperature differences.

Each of these methods requires specialized and often proprietary equipment. Additional specialty equipment may be needed for in-depth tunnel inspections and for conducting mechanical and electrical equipment checks.

4.8.3 **Robotic Inspection**

There are numerous applications for remotely operated vehicles (ROV) for inspection of tunnels. An exhaust tunnel, in-take tunnel or a suspended ceiling may be efficiently inspected by high-resolution video camera attached to sufficiently nimble robotic equipment. Infrared technology can also be added to these devices. ROV inspections can be performed in tunnel sections where there is low oxygen, poisonous gases, dusty conditions from ventilation, or unsafe access for an inspection team.

ROV data collection technology provides safe and relatively accurate dimensioning of voids, leakage points or debris fields in confined spaces. Nevertheless, any nondestructive tests performed by the ROV are usually calibrated against some sort of visual observations to increase their accuracy and reliability. Cameras, sensors, lights, and other devices are commonly included on the platform of the robot. Common types of sensors include water, gas, and obstruction detectors. The robotic equipment can be set up to be operated by remote control. If tracks are permanently mounted within sections of a tunnel, the robot or drone can perform the inspection while the tunnel is in operation. Wheeled and tracked vehicles can also be used.

4.9 Inspection Techniques for Highway Tunnels

Inspectors should understand how defects impact the function and capacity of tunnel systems. Tunnel inspectors should be able to recognize the common deficiencies that impact the structural, civil, and functional systems. The observations and measurements used to carry out the inspection should be comprehensive. For each NTI tunnel element, the SNTI defines the general extent of deficiencies for each of the four condition states: good, fair, poor, and severe.

When taken as a whole, the element level data collected during the tunnel inspection will provide information on the overall safety and reliability of the structural, civil, and functional systems. The structural elements contained in the NTI database include 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. The civil elements included in the NTI database are roadway wearing surfaces, traffic barriers, and pedestrian railings. The functional systems contained in the NTI database include the mechanical, electrical and lighting, fire and life safety, security, systems, sign, and protective systems. The written inspection procedures should cover all of these systems as appropriate for the particular tunnel.

4.9.1 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 are not contained in the NTI database but 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 also consult with the tunnel owner to develop procedures for inspecting any additional owner-defined elements.

4.9.1.1 Structural Materials

Structural elements are comprised of materials like steel, concrete, timber, and masonry. A number of material evaluation techniques are covered in the MBE. These 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 gaging performance and indicating potential problems.

In addition to any 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 making 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 a 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.

General inspection techniques are discussed below for common structural materials (e.g., steel, concrete, timber, and masonry).

I. 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.

(1) Corrosion

Corroded steel varies in color from dark red to dark brown (Figure 4.13). Initially, corrosion is fine grained, but as it progresses, it becomes flaky or scaly in character. 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 should be recorded as well as the member section remaining.

Figure 4.13 – Minor corrosion along roof girder.

(2) 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, and welds.

(3) Buckles and Kinks

Buckles and kinks develop mostly because of damage that arises from thermal strains, overload, or other load combinations that produce failure or yielding of the steel such as from collision damage, fire damage, or soil interaction.

(4) 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 that open up the joint may be taking place.

(5) Protection System

Steel is often protected by paint or galvanizing. Weathering steel can also be used. Paint systems fail by 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 defects.

II. <u>Concrete Structures</u>

Some 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).

(1) 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. The scaling is considered light when the coarse aggregate below the surface is not exposed; however, the scaling is considered severe when the coarse aggregate is clearly exposed.

(2) 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. Cracks may be active or dormant. If the crack is active, it will propagate in length, width or depth over a measured period of time. If the crack is dormant, it will not change with time; however, some dormant cracks can further degrade if not repaired as moisture penetrates into the crack causing additional damage from exposure to freeze/thaw cycles.
The direction of the crack relative to axis of structure should be observed and measured. The location, width, length, depth, and the spacing between cracks should be measured and recorded. Based on various observations and measurements, the cracks can be classified. The common types of cracks found in tunnels include longitudinal, transverse, vertical, diagonal, and random cracks.

- Transverse Cracks – These are fairly straight cracks that run roughly perpendicular to the span direction of the concrete member. These cracks vary in width, length, depth, and spacing. Transverse cracks may extend partially or completely through an element (i.e., slab, beam, curbs).
- Longitudinal Cracks – These are fairly straight cracks that run parallel to the span of the concrete slab or beam. These cracks vary in width, length, depth, and spacing. Longitudinal cracks may extend partially or completely through an element such as a slab, beam, or other element.
- Horizontal Cracks – These cracks occur in walls and vertical members but may also exist on the sides of beams where there are either encased steel flanges or corroded reinforcement. These cracks are similar to transverse cracks.
- Vertical Cracks – Vertical cracks occur in walls and other vertical members; these cracks are similar to longitudinal cracks.
- Diagonal Cracks – These cracks run at roughly diagonal angles relative to the centerline of the structure and are usually parallel to each other, shallow in depth and vary in length, width, depth, and spacing. When found in the vertical faces of beams, they signify the existence of a potentially serious problem.
- Pattern or Map Cracks – These are interconnected cracks that form a network, which vary in size and depth as shown in Figure 4.14. The width of these cracks ranges from barely visible, or fine-cracking, to well-defined, open cracks. These cracks are commonly found in members with broad surfaces such as slabs and walls.
- D-Cracks – D-cracking refers to cracks in a concrete caused by freeze/thaw deterioration of aggregates. D-cracks are closely spaced cracks that begin to form parallel to longitudinal and transverse joints, afterwards, these cracks proliferate outward away from the joints toward the interior of the element.
- Random Cracks – These are meandering irregular cracks on the surface of concrete. They have no particular form and do not necessarily fall into any of the classifications described above.

Figure 4.14 – Map or pattern cracks on the underside of an invert slab.

(3) Delamination

As the concrete hardens, water and air that is 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 types of voids create weakened zones below the surface that can eventually detach and lead to concrete spalling. This is one area of the concrete surface that produces a hollow sound when struck by a hammer. Determine the extent of these areas and document them.

(4) Spalling

Spalling is the detachment of hardened concrete fragments that leave 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 (Figure 4.15). The inspector should record the location, width, length, and depth of the spalled area and note any exposed reinforcing.

Figure 4.15 – Concrete spalling with exposed reinforcing steel.

(5) 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.

(6) 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.

(7) Mud Balls

These are small holes that are created in 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.

Figure 4.16 – Moderate cracking and efflorescence on the underside of the liner.

(8) 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. Efflorescence may also occur because of contaminates in the ground water or de-icing salts. Salt crystal stalactites can form on tunnel ceilings from severe efflorescence (Figure 4.16).

(9) Staining

Staining is a discoloration of the concrete surface caused by the passing of dissolved materials through cracks and re-depositing the materials 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 reinforcing.

(10) Honeycomb

Honeycombing occurs in concrete when the mortar does not completely fill the voids between coarse aggregate particles. Since the shape of the aggregate is visible, it gives the concrete the honeycombed appearance.

(11) 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.

III. Timber Structures

(1) Decay

Decay is the primary cause of timber deterioration; it is produced by living fungi that feed on the cell walls of timber (Figure 4.17). Molds, stains, soft rot (least severe), and brown or white rot (most severe) are common types of fungi that cause decay in timber materials. 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.

Figure 4.17 – Examples of defects in timber liners

(2) 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, and this dust should be noted. Photographs of the insect mounds may be used to document the extent of damage. Termites and carpenter ants are common types of insects that can cause timber deterioration.

(3) Checks/Splits

Checks are cracks in timber, which extend partially through the timber member; the percentage of penetration through the members 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 seasoning of the timber and should be noted in the inspection report.

(4) 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 a time consuming process. The best way to ascertain the extent of damage is to chip away at the charred remains in several locations and then measure the section remaining in the undamaged timber. The greatest section loss often occurs where two or more members have been fastened together.

(5) Hollow Area

A hollow area usually indicates either advanced decay in the interior of a 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 area hollowed.

(6) Leakage

Leaks occur in timber where water is penetrating through a joint, check, split, or some other defect in the timber such as a knot.

IV. Masonry Structures

(1) 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.

(2) 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.

(3) 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.

(4) 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.

(5) Leakage

Leaks often occur in regions of the masonry where water penetrates through joints, cracks, or other imperfection. Efflorescence accumulations might help locate areas with active leaks.

4.9.1.2 **Liners**

Tunnels liners were discussed in Chapter 1 of this manual. 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 similar to that shown in Figure 4.18 with the locations of deficiencies noted. A geotechnical engineer should determine if the ground conditions are contributing to the problems and recommend solutions.

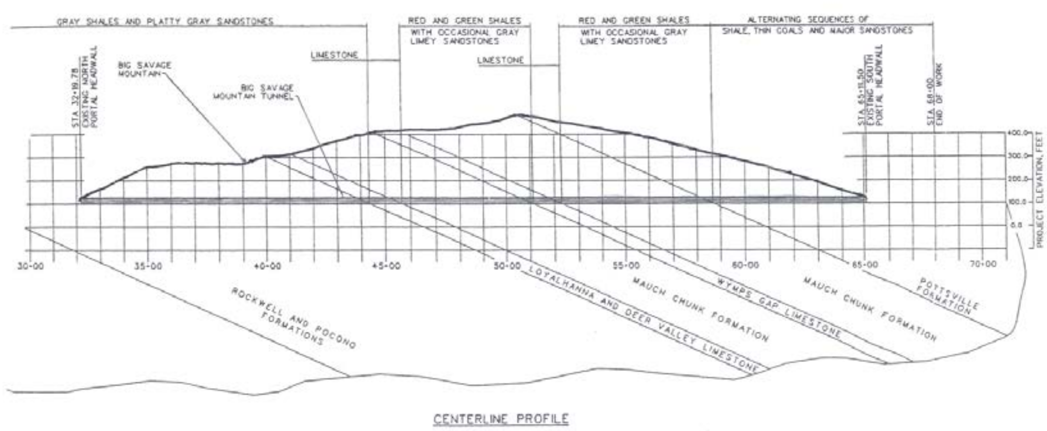

Figure 4.18 – Sample profile of geologic ground conditions.

Steel Liners – Structural steel is often 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 springline to prevent rocks from falling onto the roadway, see Figure 4.19. 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, then these steel elements should be inspected using the methods described previously for structural steel materials.

Figure 4.19 – Steel liner plate above the springline.

Concrete Liners and Shotcrete – Precast concrete liners (Figure 4.20 A) and cast-in-place concrete liner (Figure 4.20 B background) make up the bulk of all permanent final lining systems installed in highway tunnels. Because of its 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 commonly used for temporary support and as final liners in lightly loaded structures (Figure 4.20 B foreground) such as a rock tunnel that supports only the loose rock that could fall onto the roadway.

Figure 4.20 A – Example of precast tunnel liner segments.

Figure 4.20 B – Shotcrete tunnel liner foreground with adjacent cast-in-place liner concrete liner background.

Photos of some typical deficiencies in concrete liners are shown in Figure 4.21 and Figure 4.22. 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 (Figure 4.23). 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 it should be done 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 there is exposed reinforcing steel, the amount of section remaining should be noted; also, provide the percentages of section loss. 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.

Figure 4.21 – Cracks with rust stains.

Figure 4.22 – Medium width crack in concrete liner.

Figure 4.23 – Water leakage through tunnel liner and missing wall tiles.

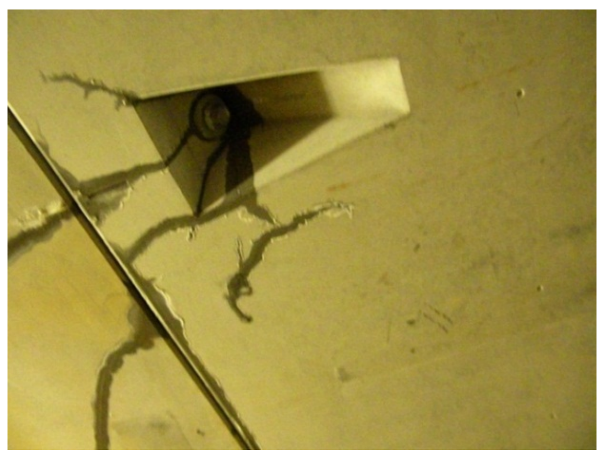

Figure 4.24 – Damp cracks in segmental liner due to improper installation techniques.

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 (Figure 4.24). Joint hardware such as end plates, bolts, and gaskets should also be inspected for each segment.

- 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 section.

Timber Liners – Timber liners (Figure 4.25) 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.

Figure 4.25 – New timber rib and lagging liner.

Figure 4.26 – Timber liner in state of deterioration.

Masonry Liners – Masonry tunnel liners have not seen much use for highway tunnels since this method was largely supplanted by concrete technology that came into existence before many highway 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 often 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. Figure4.27 shows unlined rock tunnels.

Figure 4.27 – Various unlined rock tunnels.

A qualified geologist or geotechnical engineer should assist the inspection team when inspecting self-supported tunnels in rock. 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.

4.9.1.3 **Roof Girders**

A roof girder is the main horizontal support for a flat tunnel roof (Figure 4.28). The roof girders support the tunnel roof and the loads from the backfill, surcharge, and traffic above. Girders are used to support a deck system (Figure 4.29), and these girders can be steel or concrete. Inspect these elements using the methods previously described for structural concrete or steel materials.

Figure 4.28 – Typical roof girder bay.

Figure 4.29 – Exposed roof girders.

4.9.1.4 **Columns and Piles**

Columns and piles are vertical load bearing elements that are usually comprised 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. Figure 4.30 shows a typical set of columns with a bent cap. Inspect these elements using the methods previously described for structural steel and concrete materials.

Figure 4.30 – Columns with bent cap.

4.9.1.5 Emergency Corridors

Figure 4.31 – Emergency corridor with minor leakage.

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 ideally be slightly pressurized to maintain positive air flow to prevent smoke from entering the escape route, which helps to maintain a tenable environment for evacuees and emergency responders.

The inspector should check for cracks, delaminations, and spalls in the concrete walls, ceilings, and floors. Check for leaks (Figure 4.31). Look for build-up of maintenance debris in the rooms. Examine the utilities, lights, and electrical conduit, and any 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 of the structural connections, doors, windows, frames, roofs, floors, curbs and walkways, staircases, brackets and supports, and structural finishes.

4.9.1.6 Interior Walls

The tunnel liner is in contact with the ground; whereas, 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 unique identification of interior walls and the survey control processes for reporting inspection findings. Figure 4.32 shows an emergency egress corridor, lined with concrete interior walls.

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 at areas adjacent to defects. When hollow sounding areas are detected, the limits of these areas should be defined. Mark out these

Figure 4.32 – View down emergency corridor. Wall on right is interior wall; wall on left is tunnel liner.

areas using keel or paint. Note the size, maximum depth, and location of the spalls; and note 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.

Figure 4.33 – View of tunnel with metal panel finish covering concrete liner.

Architectural Finishes – Many concrete tunnel walls are not visible because they are covered by architectural finishes such as ceramic tiles or metal panels (Figure 4.33). Tile walls should be checked for cracked, delaminated, or missing tiles that could indicate defects in the underlying substrate concrete. Missing tiles may be the result of moisture and water penetration through the concrete substrate. Check the exposed substrate concrete for cracks, delaminations, 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.

4.9.1.7 **Portals**

Tunnel portals are located at the entrances and exits of the tunnel (Figure 4.34). When inspecting the portal facades, it is important to consider the condition of the elements that are above the roadway since spalls or falling objects from above could impact the safety of tunnel users. It is also important to document the condition of material outside and above the portals, especially if there are concerns for 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, delaminations, 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 build-up of debris in the rooms. Examine the utilities, lights, and electrical conduit within the rooms for deterioration. Miscellaneous structural checks should be performed on all of 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.

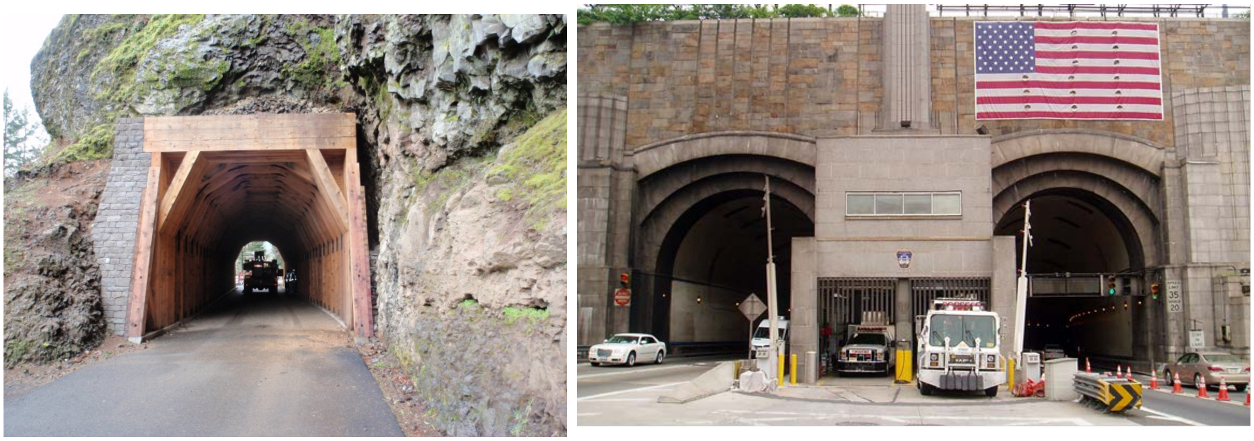

Figure 4.34 – Tunnel portals range from simple (left) to complex (right) structures.

4.9.1.8 **Tunnel Ceiling Structures**

Tunnel ceiling structures consist of slabs or panels that are supported by 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 either exhaust or supply air to the tunnel. Sometimes the upper plenum also contains utilities.

The configuration of the upper plenum depends on the shape of the tunnel. For example, a circular tunnel will have roughly a half moon shape, while a box tunnel will have a box-shaped plenum, see Figures 4.2 through 4.4. 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 that are 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 these objects to fall onto the roadway below. 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 conducting an inspection of ceiling elements, the inspector should review all pertinent drawings and procedures.

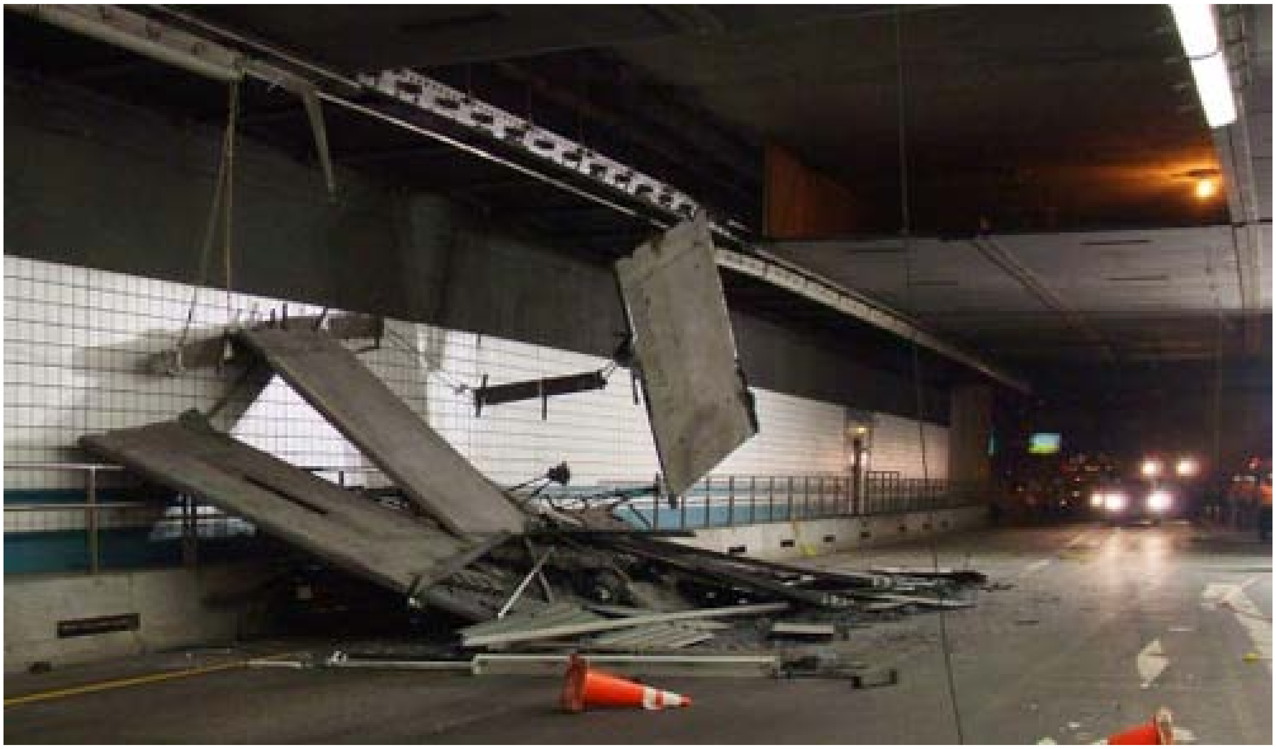

Figure 4.35 – Overhead items such as ceiling panels must be inspected to prevent fatalities.

Hangers and Anchorages – If the ceiling structure is supported with hangers and anchorage 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.* The inspector should refer to FHWA Technical Advisory T 5140.30, which superseded T 5140.26. A copy of this document is found at the link below:

http://www.fhwa.dot.gov/bridge/t514030.cfm

If anchors have pulled out or are loosening, the tunnel owner should be immediately notified since this poses a significant safety concern (Figure 4.35). 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. Figures 4.36 and 4.37 show some common defects in hangers.

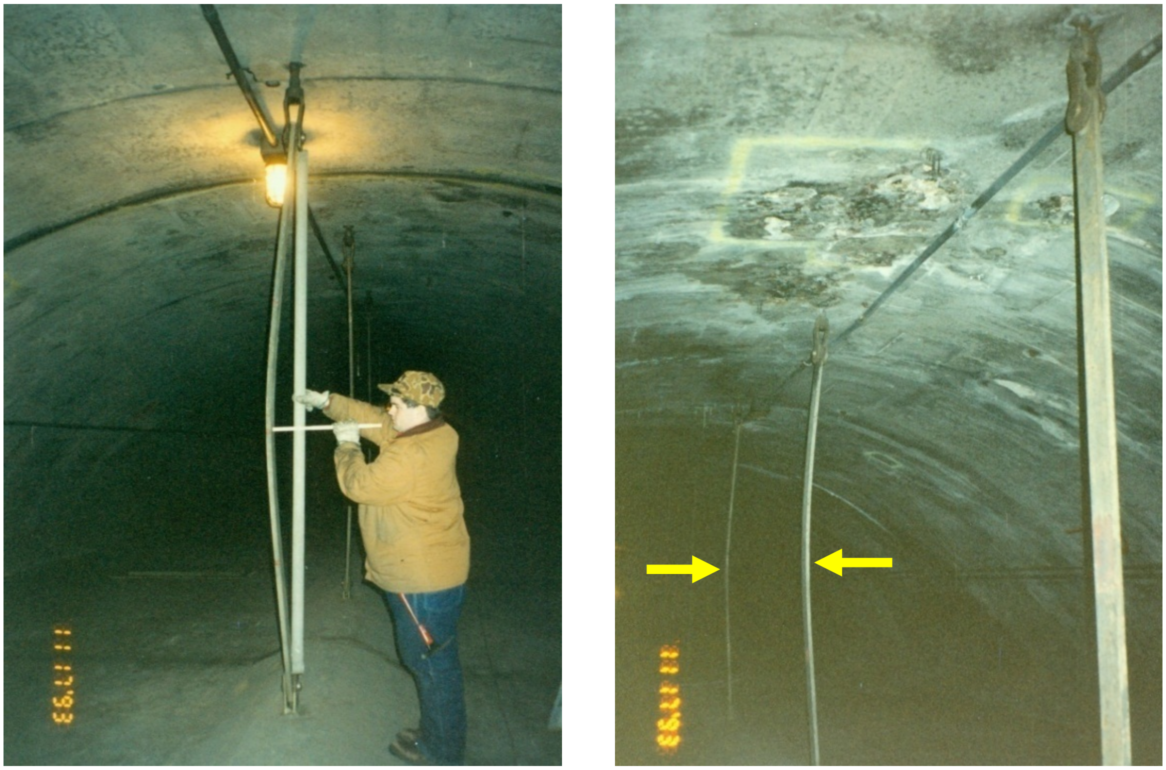

Figure 4.36 – Bent ceiling slab hanger.
Note: Successive hangers are bent.

Figure 4.37 – Hangers and ceiling girders exhibiting moderate to heavy rust and minor section loss.

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 any of the embedded supports or exposed anchors.

Visually inspect the hangers to determine if they are bowed. A bowed hanger possibly indicates that the ceiling slab was pushed up from either 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 after being 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, delaminations, 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 (Figure 4.37). 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 any 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 any spalls and document the section loss (Figure 4.38). Visually inspect for moisture and corrosion staining at cracks; and note efflorescence at crack locations.

Figure 4.38 – Delaminated and spalled concrete with deteriorated and exposed reinforcing steel on underside of concrete ceiling slab.

An architectural finish may be placed on the underside of the ceiling slabs or panels in some cases (Figure 4.39). If ceramic tiles, concrete-filled metal pans, or steel composite metal pans make up the underside finish, their condition is evaluated more rigorously than on the walls, since delaminated tiles can fall onto the roadway. Check the ceramic tile finish for cracked, delaminated or missing tiles, which could indicate defects in the substrate concrete. Examine any exposed substrate concrete for cracks, delaminations, and spalls.

Figure 4.39 – Examples of damaged and deteriorated architectural finishes on underside of ceilings. Photo left is of damaged metal ceiling panels; right is deteriorated ceramic tile.

4.9.1.9 **Tunnel Invert Structures – Slabs, Girders, and Slabs on Grade**

Tunnel invert structures consist of slabs that are supported by girders or on grade. When the roadway is a structurally supported slab, then 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, delaminations, 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 prior to making recommendations for repair or replacement. Document the length, width, and location of all cracks and delaminations. 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 delaminations. 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; and robotic video inspection techniques can be used for inspecting tight spaces like these. Examine the concrete slabs for cracks, delaminations, and spalls. Use a hammer to sound random areas of concrete for delaminations, 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 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.

4.9.1.10 **Joints and Gaskets**

Joints are integral to many structural elements and are 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, at the connections to ancillary buildings, and at auxiliary structures. Check the concrete around the joint for cracks, spalls and delaminations. 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 any 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 types of gaskets such as lead, mastic, or rubber. Gasket materials can become dislodged from the joint due to water infiltrating though the joint, loosening of fastening bolts, etc. Gaskets can also fail due to chemical or biological deterioration of the material. Structural movements of the liner can also 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 such as 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, or leaks of any kind.

4.9.1.11 **Miscellaneous Structural Checks**

Although these items are not specifically reported to the 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 any auxiliary structures. These items should be included in the written inspection procedures developed by the tunnel owner.

Structural Connections – The 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 be helpful for detecting cracks. Coatings may protect welds from corrosion.

Doors – During the inspection, all of the doors and windows encountered should be opened and closed to verify their operability. Some door components may be deteriorated, stuck, or inoperable (Figure 4.40). The door hardware should be checked to ensure that the latches sufficiently engage the door frame and that the door can be closed securely. The door and the frame might have corrosion, delamination, or section loss. Security sensors should also be checked to be sure they are operational.

Figure 4.40 – Doors

Windows and Frames – Steel window frames may be corroded, deteriorated, or experience section loss. Some of these may be stuck or inoperable. When concrete window frames are inspected, check for cracks, delaminations, 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 (Figure 4.41). Reinforced concrete stairs sometimes have steel tread plates incorporated in 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 for loose or missing bolts. Document the severity and location of any defects.

Figure 4.41 – Stairs

Concrete Staircases – Inspectors should check concrete stairs for cracks, delaminations, 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 delaminations. 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 make note of 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 found. Note the length, location, and distance of spread of all crevice corrosion.

Figure 4.42 – Ancillary building: with metal ladders to roof.

Roof – Check the roof of any Ancillary Buildings (Figure 4.42) or Auxiliary Structures for any deterioration which would allow water to penetrate through 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 any defects or deteriorated materials. Note the location and severity of any defects on the roof. Document any locations of water penetration. Record the condition of the roof coating material and the drainage system.

Floors – Check concrete floors for cracks, delaminations, 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 area. Examine the floors for evidence of distortion and settlement. Document the length, width, depth, and location of all cracks and delaminations. 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 be helpful for detecting cracks. Photos of various brackets and supports with various deficiencies are shown in Figure 4.43 and Figure 4.44.

Figure 4.43 – Sign support with gaps at connection.

Figure 4.44 – Missing bolt at longitudinal fan support.

Machinery Pedestals – Check concrete pedestals (Figure 4.45) for cracks, delaminations, and spalls. Use a hammer to sound random areas of the 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 delaminations. Record the area, maximum depth, and location of all spalls along with the condition of exposed reinforcing steel.

Figure 4.45 – Cracked machinery

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 removal or checking loose tiles.

4.9.2 Civil Elements

The SNTI defines condition states for invert wearing surface, traffic barriers, and pedestrian railing systems (Figure 4.46). Although drainage systems are commonly considered civil systems, these are discussed under mechanical systems and pumps. Miscellaneous civil elements are not contained in the NTI database but should be inspected periodically to maintain safety.

Figure 4.46 – Typical civil elements including wearing surface, traffic barrier, and pedestrian rail and walkway.

4.9.2.1 Wearing surfaces

Tunnel roadways have either bituminous or concrete wearing surfaces on the structural invert. When inspecting the wearing surface, examine the skid resistance of the surface, look for grooving or rutting in the wearing surface. A glossy or shiny surface or exposed polished aggregate may be indicators of wear. Check that water properly drains from these surfaces. When wearing surfaces are not properly drained, they can wear prematurely and develop holes and present safety hazards to motorists. The roadway surfaces on tunnel ramps can also be impacted by high groundwater levels.

Concrete – Concrete wearing surfaces should be checked for potholes, cracking, scaling, and delamination (Figure 4.47). Look for exposed reinforcing steel. For spalls, document the size, maximum depth, and location. Also, document any exposed reinforcing steel, and identify section loss. Use a hammer to sound random locations of the concrete wearing surface and areas adjacent to cracks, delaminations, and construction or expansion joints. Document the areas and locations of delaminated concrete. Areas of delaminated concrete may spall and present hazards to traffic. Provide an estimate of total crack length as well as the average length, width, location, and spacing.

Figure 4.47 – Pothole with cracking in concrete wearing surface.

Asphalt – Asphalt wearing surfaces should be checked for cracking, wheel path rutting, surface irregularities, and potholes. Use a hammer to sound random locations of the wearing surface. Note any dull thuds, which could be indicators of future potholes. Also, investigate whether the pavement is drying out, and verify a good seal between the wearing surface and the curbs.

4.9.3 **Traffic Barriers**

At roadway level the tunnel walls are typically protected from errant vehicles by concrete curbs and barriers. These barriers are usually concrete; however, their vertical surface may be covered with ceramic tiles. A concrete safety walkway is usually provided in the tunnel bore. Document the length, width, and location of all cracks and delaminations. Record the area, maximum depth, and location of all spalls along with the condition of the reinforcing steel if it is exposed. Document the severity and locations of all other defects including moisture penetration, efflorescence, and corrosion staining. Sample photos of these elements with various deficiencies are shown in Figure 4.48.

Figure 4.48 – Traffic barriers.

4.9.3.1 **Pedestrian Railings**

Pedestrian railings are common where raised sidewalks are used. These are commonly constructed of tubular steel, stainless steel, or aluminum with posts spaced along the walkway to support the lateral railing, and it can be produced using pipe, W-beam, or other shapes. The railing members can be coated with a structural finish such as paint or galvanized metal. Railings are a safety measure to prevent personnel on top of the walkway from falling into vehicles in the adjacent traveled lane. All aspects of the railings should be inspected and deficiencies noted.

During inspection, check the rails, posts and anchorages. Examine the railing for vertical and horizontal misalignment, missing or broken sections, impact damage and deterioration such as cracks or corrosion with section loss. Inspect for cracked welds at the connections and loose or missing bolts. Section loss can be found most commonly in the base of the posts and the anchor bolts, especially if debris accumulation is present. Evaluate the condition of the paint or galvanizing. Document the location and severity of any defects. Sample photos of typical types of deficiencies are shown in Figure 4.49 and Figure 4.50.

Figure 4.49 – Bent post and missing mid-rail.

Figure 4.50 – Bent pedestrian railing with missing railing components.

4.9.3.2 **Miscellaneous Civil Checks**

Although these items are not specifically reported to the FHWA, it is good practice to perform miscellaneous civil checks on all curbs and sidewalks in the tunnel, ancillary buildings, or ancillary structures. These items should be included in the written inspection procedures.

Curbs and Safety Walkways – Curbs and safety walkways protect the tunnel operation and maintenance staff and users who need to evacuate during emergency conditions.

Curbs – Curbs are typically constructed of concrete. Check the curbs for proper alignment. Improper alignment or a protruding curb section can become a safety hazard for vehicles.

Visually examine these elements for any buildup of dirt or debris that may reduce their effectiveness to transport the surface runoff into the drainage system. Examine the curbs for cracks and spalls. Check spalled areas for exposed reinforcing steel and document any section loss in the steel.

Walkways – The inspector should look for cracks, scaling, delaminations, spalls, tripping hazards, debris accumulation, and ponding of water. Examine spalls for exposed reinforcing steel and report any section loss. Advanced cracks and spalls can undermine the structural integrity of the safety walkways. Document the size and locations of any defects found. Document the length, width and location of all cracks and delaminations. Record the area, maximum depth and location of all spalls along with the condition of the reinforcing steel if it is exposed. Document the severity and locations of all other defects including moisture penetration, efflorescence, and corrosion staining.

Emergency Egress **–** The quality of the walking surface on every safety walkway or emergency egress should be examined. Under emergency conditions, these walkways may be used for self-rescue or by first responders. Check for locked or inoperable doors and access to refuge areas, considering that some users have reduced mobility. Note in the inspection documents any deficiencies found.

Maintenance walkways – Some of the more complex tunnels have concrete or steel maintenance walkways. Inspect these in accordance with procedures for other steel and concrete elements.

4.9.4 **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 are not contained in the NTI database but 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 prior to conducting inspections on mechanical systems. The inspectors should verify the performance of any repairs or replacements noted in the logs. Table 3-4 provides a generalized list of mechanical system maintenance checks that should be reviewed prior to conducting the inspection.

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 to 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 in accordance with established communication protocols. Boiler units and pressure vessels can be dangerous; it is recommended that qualified specialists or specialty contractors be used as appropriate.

4.9.4.1 **Tunnel Ventilation**

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

Tunnel ventilation systems incorporate several mechanical components such as fan motors, louvers, motor-operated dampers, and various drive trains. The fans can be centrifugal or axial (Figure 4.51). 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, 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.

Figure 4.51 – Axial fan, left and centrifugal fan, right.

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 (Figure 4.52). Check the motor housings, supports, and surrounding components for grease accumulation. Check the seals to see if they have failed or if they 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 any unusual noises such as humming or screeching from the motor or bearings. Listen to and feel the motor housing for any abnormal vibrations or temperature.

Figure 4.52 – Staining on the fan pedestal is evidence of lubrication leak.

Tunnel fans should be operated on 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 operating temperature of the motor. 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 or drive housings or on the 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 the oil or lubricant that is leaked isn’t presenting a fire hazard.

Noise and Vibration: Any excessive noise or vibration should be noted. If possible, identify the source of 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 any 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 as 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. These are common with axial fans. Indirect drive fans have gears that are driven by belts or chains and sprockets. These 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 (Figure 4.53), check the housings for paint failure and surface corrosion. Examine the housings for oil leaks at any splits or covers. Check the condition of the oil and the oil level in the housing. If possible, open up 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 that the chain is loose. The chain should be taut.

Figure 4.53 – Chain and sprocket drive.

Fan Shaft Bearings – Bearings are critical components for fan operation. Bearing life is usually 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, 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 grease accumulation on adjacent components. 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 change and excessive heat build-up in bearing or drive.
- Dirt contamination caused by not properly sealed bearing or drive; or by lubricating oil not properly stored or handled prior to use.
- Metal-to-metal wear indicated by 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 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 temperature. Check extended grease lines for condition and breakage.
During operation, listen for any abnormal sounds, and watch for any abnormal movement or vibrations which indicate possible defects. If possible, diagnose the cause or 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, delaminations, or other defects.

Figure 4.54 – Corroded fan housing.

Fan Housings – The inspector should check all components of the fan housings for failed paint, corrosion, and section loss (Figure 4.54). 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 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 the 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 any testing tags that may indicate defective equipment.

Figure 4.55 – Damper blade arrows should point in the same direction.

Dampers and Damper Drives –Verify that the damper drives are operational (Figure 4.55). Check the door chains for signs of distress (Figure 4.56). Ensure that the louvers and the damper doors close completely (Figure 4.57). 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.

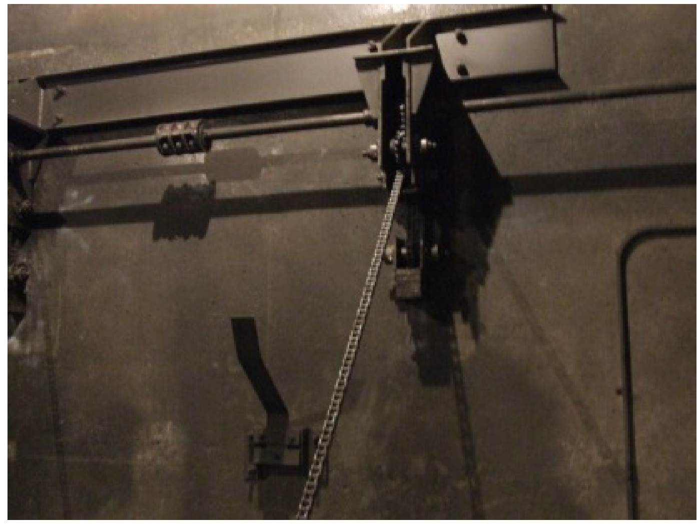

Figure 4.56 – Door chains.

Figure 4.57 – Louvers in closed position, left; louver with large gap when closed, right.

Sound Attenuators – Noise from the fan 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.

4.9.4.2 **Tunnel Drainage**

The tunnel drainage system is designed to remove water from the roadway and is made up 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 (Figure 4.58). 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.

Figure 4.58 – Broken scupper grate.

Operate all pumps to verify that they are all functioning properly (Figure 4.59). 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.

Figure 4.59 – View inside pump room.

Figure 4.60 – Moderate corrosion to pipes, pipe supports and fasteners.

Manually run the pump from the local control panel as well as any remote panel. If possible, with the control in the ‘auto’ position, manually raise the sump float to activate the pump. 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 (Figure 4.60). 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 on pumps rated over 5 horsepower.

Observe the general condition of the pump, motor, supports, and guards. Note the percentage of clean and painted surface as compared to rusted and deteriorated surface. 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 piping for security and installation of vibration control and expansion devices. Note any significant leakage around pump seal for base-mounted pumps. Observe any leakage of 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 submersed in water and pumps water from a collection basin (Figure 4.61), which are 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 their 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 obtain a working understanding of how the drainage system works and where the sump pits are located.

Figure 4.61– Accumulation of calcium deposits at sump pump.

All of the pump components, related supports, and system piping should be checked for damage, corrosion and deterioration. Inspect for excess calcium deposits on all of the components. 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 excessive 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.

4.9.4.3 **Emergency Generator System**

A standby generator is a back-up electrical generator system that operates when the power grid fails to deliver electricity. Emergency generators (Figure 4.62) may operate on gasoline, diesel fuel, natural gas, or propane.

Generators with internal combustion engines produce dangerous carbon monoxide (CO) gas, which can be deadly if inhaled. Check that the exhaust is properly vented. Natural gas or liquid propane fuel can accumulate to dangerous levels if leaks in fuel supply are not properly vented to the atmosphere.

Figure 4.62 – Emergency Generator.

Emergency generators are used to supply enough electricity to operate the essential equipment and to 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, 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 percent, 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.

4.9.4.4 **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 gate house, lifting mechanism, flood gate, seating mechanism in roadway, dewatering valve, and drainage shut-off valve. The gates themselves are constructed of steel and are designed to withstand the hydraulic forces during a flood event. Figure 4.63 shows a typical flood gate.

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 that is 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.

Figure 4.63 – Flood gate.

4.9.4.5 **Miscellaneous Mechanical System Checks**

Although these items may not be specifically reported to the FHWA, 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 – The components for HVAC elements in support spaces consist of fans and dampers, filters and coils, and controls. The

HVAC equipment should be operated in all speeds and all modes. Confirm change-over from heating to cooling modes occurs as the thermostat is cycled. Confirm fan operation, note any vibration or unusual noise. Observe damper operation noting any 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 temperature/comfort level of space served by the unit. Confirm the unit is maintaining the temperature set point. Cycle thermostat and observe 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 percentage of clean and galvanized/anodized/painted surface as compared to rusted and deteriorated surface. 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 temperature at the time of the inspection may limit operation or proper verification.
- Perform vibration analysis and inspections on chillers, cooling towers, and pumps.
- At time of 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, deaeration, steam traps) are functional and operating properly and efficiently.

- Verify that the system is operational. Note that temperature at the time of the inspection may limit operation or proper verification.

4.9.5 **Electrical and Lighting Systems**

The SNTI defines the elements required for the NTI including the electrical distribution system, the emergency distribution system, 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 any recent repairs or replacements noted in the logs. Table 3-5 provides a generalized list of electrical and lighting system maintenance checks that should be reviewed prior to conducting the inspection.

The tunnel inspection organization should develop written procedures for the elements listed in the SNTI 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 for electric shock.

4.9.5.1 **Electrical Distribution Systems**

Electrical systems are complex and contain multiple components that are potentially hazardous. The existing records and schematics should be carefully reviewed prior to conducting an inspection, and it is important that the inspectors understand of the system thoroughly. Determine the need to conduct any 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 individual components of the system.

Figure 4.64 – Electrical fire.

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 (Figure 4.64).

- 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 that they trip correctly.
- Examine the conduit support structure, including all clamps and supports. Ensure all conduit clamps are secure (Figure 4.65).
- 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.

Figure 4.65 – Electrical conduits with heavy corrosion and section loss.

Figure 4.66 – Electrical equipment: Single phase insulated transformer.

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 to 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. Any 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 (Figure 4.66), 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 as well as operation of the equipment, maintenance reports and daily logs, and any in-depth testing procedures (e.g., thermographic inspection, contact resistance testing, and generator load testing).

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 surface as compared to rusted and deteriorated surface. 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 the FHWA, it is good practice to perform electrical systems check on all miscellaneous electrical components and appliances in the tunnel, equipment rooms, maintenance corridors, plenums, ancillary buildings, and auxiliary structures. Check the condition of any electric receptacles, wires, switches, circuit breakers, meters, etc. for evidence of overloading, overheating, damage, deterioration, and corrosion. Look for evidence of arcing, discoloration, or other signs that might indication the electrical components are defective. These items are commonly included in the owner defined elements.

4.9.5.2 **Emergency Power Distribution Systems**

NFPA produces documents that are useful for maintaining, inspecting, and testing emergency power systems to include *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 (Figure 4.67). 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 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.

Figure 4.67 – Emergency power supply.

4.9.5.3 **Lighting Systems**

Lighting systems are complex elements consisting of multiple components with potentially hazardous equipment (Figure 4.68). A failure of some components may limit the effectiveness of the system 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 use and emergency use, it may be useful 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 (Figure 4.69). 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 observing the changes in the illumination levels on the roadway surface as compared to the system design criteria. Following are some processes to consider for lighting system testing:

Figure 4.68 – Maintenance and inspection of lighting system.

Figure 4.69 – Lighting control cabinet.

- 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 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 quality of washing and impacts to the lighting. Observe the general condition of the lenses and housing of the lighting luminaires. Note percentage of clean, broken lenses or housing, and corroded surfaces (Figure 4.70).

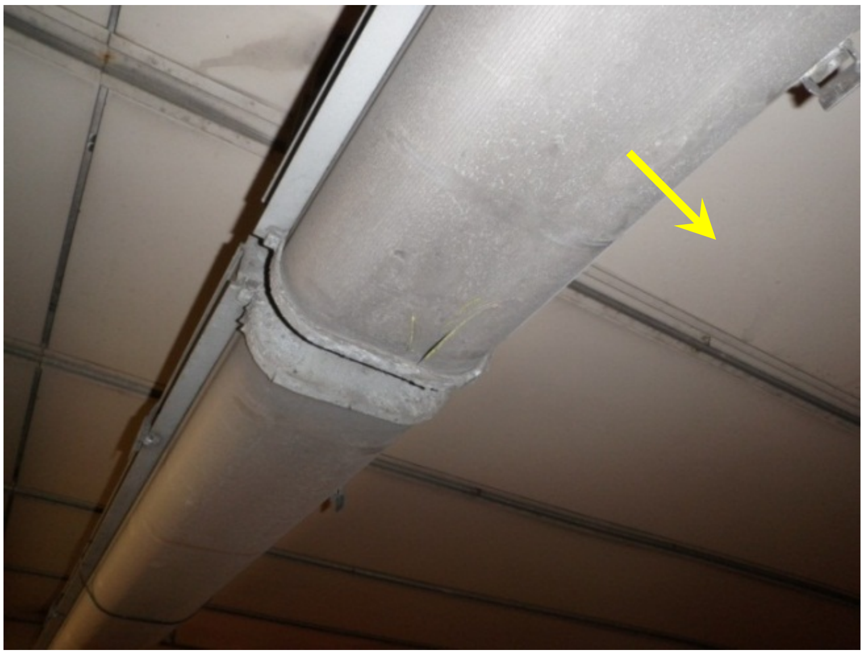

Figure 4.70 – Light fixture with damaged lens.

When inspecting lighting luminaires and their attachments, the inspector should look for corrosion damage from environmental conditions and corrosion caused by contact of 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.

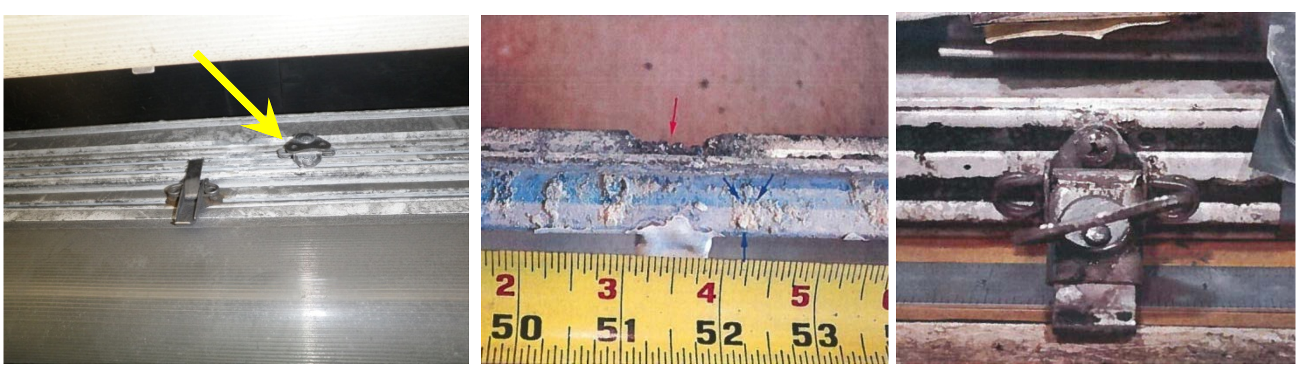

Figure 4.71 – Stainless steel clip severely corroded due to galvanic action.

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. Figure 4.71 shows a stainless steel clip completely eroded away due to a contact with dissimilar metals.

Miscellaneous Lighting System Checks – Although these items may not be specifically reported to the FHWA , it is good practice to perform miscellaneous lighting systems check 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, and they should also be checked 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.

4.9.6 **Fire and Life Safety, Emergency Systems and Operation**

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 prior to 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 damaged components.

4.9.6.1 **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 produces several documents that are useful 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, 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.

Table 3-6 provides a generalized list of fire and life safety maintenance systems checks. Maintenance logs that document these checks should be reviewed prior to conducting the inspection. Deficiencies in the log book should be noted. When inspecting fire systems, it is good practice to be on the look-out for unprotected electric wires, improper storage of flammable materials, and products, that when burned, produce toxic chemicals (e.g., plastics like PVC or HDPE materials).

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 the fire detection system include control panels, power supplies, detection devices, and notification devices such as 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 operate.
- Check existing records to determine if the system has been tested at regular intervals in accordance with NFPA 72. Review the records available for the last seven years.
- Review the maintenance/inspection records for the system 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 (Figure 4.72) and that the expiration date, pressure, and seal are present on portable fire extinguishers. A fire suppression system, such as a

Figure 4.72 – Missing fire extinguisher.

sprinkler system (Figure 4.73), 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.

Figure 4.73 – Foam sprinkler system test.

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 by other qualified fire system inspectors.

4.9.6.2 **Emergency Communication Systems**

The components of the emergency communication system include cameras and camera systems (CCTV), intercom, radios, cell-phones, receivers, wiring, computer analytics, and other technology. Inspection requires testing the communication devices in simulated emergency conditions. This requires examination of issues like system interoperability, scenario-based exercises for different emergencies and conditions, interagency cooperation for response, and even cyber-security. Inspection also includes visual and technical examination of hardware by specialists.

Figure 4.74 – Examples of CCTV camera systems.

4.9.6.3 **Tunnel Security and Operation Systems**

The systems included under security and operation involve surveillance, control, and communication equipment such as CCTV cameras (Figure 4.74), telephones, radios, incident response and detection devices (Figure 4.75), 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 any over-height detector systems (Figure 4.76) are not triggering at any heights just below the desired setting and also verify that they are triggering at or just above the desired setting.

Figure 4.75 – Detection equipment.

Figure 4.76 – Over-height detection screen.

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 programed to operate the tunnel facility at optimum levels. SCADA systems operate with a minimal amount of hardware maintenance, with the exception of the component level sensors. Software changes for additional programming and periodic upgrades are required to maintain flexibility and reliability of system operation.

4.9.7 **Signs**

Traffic signs, egress signs, variable message boards, and lane signals and fixtures are included in the NTIS. These elements are used to display information and communicate with the driver so that good decisions can be made when entering, traveling though, and exiting the tunnel for both normal operations and during emergencies.

Figure 4.77 – Damaged sign.

Variable message boards, traffic control devices, and lane signals require written inspection procedures and qualified electrical inspectors because of the dangers posed by electric current and the complexity of these elements.

Figure 4.78 – Malfunctioning sign.

Traffic and Egress Signs – Inspect signs for reflectivity and clarity, impact damage (Figure 4.77), vandalism, deterioration, and attachment to the tunnel structure. If signs or components are missing, this should be noted. Certain signs are electrically illuminated and contain bulbs (Figure 4.78); therefore, the inspection will need to verify that the sign has power and is functional.

Check for corrosion, cracks, buckles, and kinks. Particular attention should be given to bolts in regions where leakage occurs. Document the loss of section and missing or loose bolts.

Traffic Control Devices – Tunnel traffic control devices can be mounted on the tunnel walls, the overhead ceiling, or on the barriers at the portals. These devices are either reflective signs or illuminated display signs using electrified light bulbs. When electric current is involved, check for dissimilar metals, which may corrode metals at accelerated rates when these metals are not sufficiently insulated.

Check the signs for traffic impact damage. Look for missing signs. Verify that the signs have not become illegible from impact damage, vandalism, deterioration, loss of retroreflectivity, or other causes. For illuminated display signs, verify that the sign has power and is functional. Examine the display messages. Check the supports for corrosion and section loss.

Variable Message Boards – Variable message boards or signs (VMS) are electronic traffic signs that are used to convey changing information about events such as traffic congestion, accidents, incidents, roadwork zones, lane closures, speed limits, and emergency conditions. The messages are limited by the type of technology used and by the configuration of the display board (Figure 4.79). The structure is commonly constructed of aluminum and treated with an antiglare facing. Flashers or beacons are devices that are used to draw attention to a sign when an important message is being displayed. These should also be checked.

Figure 4.79 –Typical variable message boards.

In order for these message boards to be effective, the lettering must be legible, and the bulbs that form the letters of the words should be checked. These devices can be complex with display modules, drivers, power supplies, sensors, fans, dust filters, control cabinets, controllers, input/output circuit boards, modems, and computerized controllers. The frames and mounting hardware should be checked carefully. Check for corrosion, dissimilar metals, cracks, buckles, and kinks.

Lane Signals and Fixtures – The components of the tunnel lane signal system include the lane signals themselves (Figure 4.80), the control system, and interfaces to other systems, such as fire detection. The lane signal system conditions should be inspected using a combination of visual observations and measurements. When electric current is involved, check for dissimilar metals, which may corrode at accelerated rates when they are not sufficiently insulated from stray electrical currents.

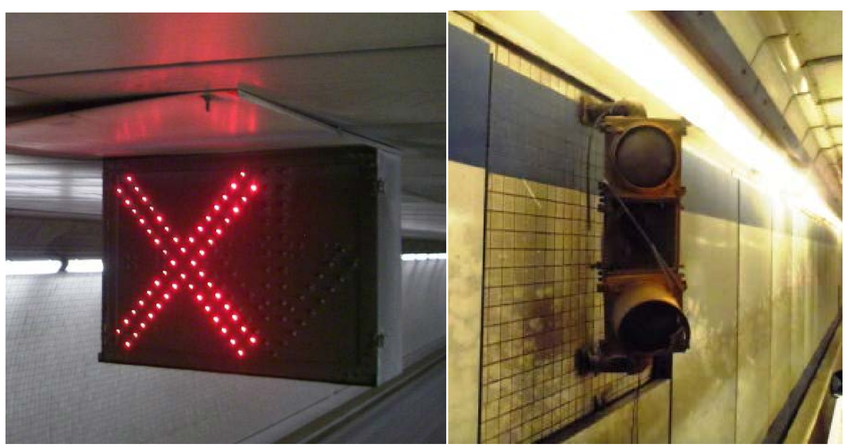

Figure 4.80 – Operable signal, left; inoperable, right.

4.9.8 **Finishes and Protective Coatings**

Protective systems such as steel corrosion protective coatings, concrete corrosion protective coatings, and fire protective coatings are included in the NTI. The interior finish of a tunnel is very important to the overall function of the tunnel. To improve safety and facilitate maintenance, tunnel finishes should:

- Be designed to enhance tunnel lighting and visibility.
- Be fire resistant.
- Not generate toxic fumes during a fire.
- Be able to attenuate noise.
- Be easy to clean.

Ceramic Tile – Ceramic tiles are the most widely used by tunnel owners because of ease of placement and cost (Figure 4.81). They are extremely fire resistant, easily cleaned, and good reflectors of light due to the smooth, glazed exterior finish; however, tiles are not effective sound attenuators. Typically, tiles are 4 ¼ in. square and can be ordered in many colors. Tunnel tile installation differs from conventional ceramic tile in that they require a more secure connection to the tunnel lining. Tiles should not be allowed to fall onto the roadway and impede or endanger users.

Figure 4.81 – Ceramic tile finish reflecting light.

Porcelain-Enameled Metal Panels – Porcelain enamel is a combination of glass and inorganic metal oxides fused together under extremely high temperatures. This method is used to coat most home appliances. The Porcelain Enamel Institute (PEI) has established guidelines for the performance of porcelain enamel through the following publications:

- Appearance Properties (PEI 501)
- Mechanical and Physical Properties (PEI 502)
- Resistance to Corrosion (PEI 503)
- High Temperature Properties (PEI 504)
- Electrical Properties (PEI 505).

Porcelain enamel is typically applied to either cold-formed steel panels or extruded aluminum panels. For ceilings, the panels are often filled with a lightweight concrete; and for walls, fiberglass boards are frequently used. The attributes of porcelain-enameled panels are similar to those for ceramic tile. These coatings are durable, easily washed, reflective, and come in a variety of colors. As with ceramic tile, these panels are not effective sound attenuators.

Epoxy-Coated Concrete – Epoxy coatings have been used on many tunnels during construction to reduce costs. Durable paints have also been used. The epoxy is a thermosetting resin that is chemically formulated for its toughness, strong adhesion, reflectiveness, and low shrinkage. Experience has shown that these coatings do not withstand the harsh tunnel environmental conditions as well as the other finish types and need to be repaired or rehabilitated more often.

Miscellaneous Finishes – A variety of other finishes can be used on the walls and ceilings of tunnels. Some of these finishes are becoming more popular due to their improved sound absorptive properties, ease of replacement, and other advantages over some of the materials mentioned previously. Some of these systems are listed below:

Coated Cement Board Panels – These panels are not widely used in the United States. The elements consist of lightweight, fiber-reinforced cement board that is coated with baked enamel.

Pre-cast Concrete Panels – This type of panel is often used as an alternative to metal panels. They may use a metal panel veneer or more commonly, ceramic tile for the final finish.

Metal Tiles – This tile system is not common, but it has been used successfully in some tunnel applications. They are coated with porcelain enamel and set in mortar like ceramic tiles.

4.10 Owner Defined Elements

Owner defined elements may be incorporated into the inspection process in order to tailor the program to the specific requirements of the tunnel owner. Plans and procedures to inspect owner defined elements should include any forms or reports needed to collect the data. Owner defined elements are useful when:

- Elements are not contained in the SNTI and inspection of this item would be beneficial to the tunnel owner.
- Elements are contained in the SNTI but more refined elements are desirable.

Geotechnical conditions play a key role in the protection of some tunnels; and the owner should evaluate the geotechnical conditions associated with the tunnel as deemed necessary; this is especially the case with tunnels that cross navigation channels. Submerged tunnels that cross navigation channels are usually covered with a layer of fill that is resistant to erosion and provides protection against impacts from sinking vessels, ship’s anchors, etc. When built, bored tunnel are usually located with sufficient protective cover. Over time, erosion and dredging can take place. As such, the geotechnical conditions should periodically be inspected.

4.11 Critical Finding and Condition State Ratings

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.

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 safety and serviceability of the element. Condition states are recorded in the inspection report and database and then submitted to the FHWA. Critical findings require immediate attention in accordance with agency and NTIS requirements.

4.11.1 **Critical Findings**

Critical findings are defined in the NTIS. 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 the FHWA within 24 hours. The FHWA should be updated regularly or as formally established as to the status of each critical finding until the issue is resolved. FHWA is to be provided with an annual summary report of the current status of each critical finding identified within the past year and each unresolved finding from a previous year.

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

- Close the tunnel until the severe defect is removed or repaired, if the 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 that describes 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 that is 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.

4.11.2 **Condition State Ratings**

Element-level inspection techniques are used to rate each tunnel element according to the SNTI. Quantities are developed for each element and condition states are assigned for the percentage of this quantity in each condition state. The four condition states, CS1, CS2, CS3, and CS4, represent good, fair, poor, and severe, respectively. Condition states for tunnel elements will typically be assigned using a particular unit of measure such as linear foot, square foot or each. Accuracy in establishing the condition states is important for safety and their utility in tunnel management systems.

Table 4.4 – Railing Element Coding Example

Element Name	**Quantity**	**CS1**	**CS2**	**CS3**	**CS4**	**Notes**
Railing	1,000 LF	700 LF	150 LF	140 LF	10 LF	No Safety Concerns
	Percent	70%	15%	14%	1%	*SNTI Defined*
Posts	*100 Each*	*75*	*10*	*12*	*3*	*Owner Defined*
	Percent	*75%*	*10%*	*12%*	*3%*	

Table 4.4 illustrates a coding example for a simple railing element. Tunnel elements may have different condition states for the same element. A tunnel with 1,000 linear feet (LF) of railing may have 700 LF of railing in good condition; 150 LF in fair condition; 140 LF in poor condition; and 10 LF in severe condition. The corresponding entry for condition states would be: 70 percent to CS1, 15 percent to CS2, 14 percent to CS3, and 1 percent to CS4. The railing posts are an owner defined subelement. Since the condition states for the post subelements were in line with that of the railing system, no adjustments were made to the overall condition state of the railing. In this particular example, there are no critical findings to report since there were no safety concerns that require immediate action.

4.12 Tunnel Inventory and Inspection Documents

Tunnel inventory and inspection data should be collected and documented using paper forms or electronic tablets; whereas, the initial tunnel inventory can be obtained from the existing records and field verified as needed. Comprehensive tunnel inspection requires field books, forms, photographs, and reports to effectively communicate and document the inspection findings.

4.12.1 **Example Inventory Form**

The preliminary National Tunnel Inventory data includes information on the tunnel identification, age and service, classification, geometric data, inspection, load rating and postings, navigation, and the structure type. Table 4.5 contains a tunnel inventory form that is compatible with the requirements contained in the SNTI.

Table 4.5 – Sample preliminary tunnel inventory data

Identification Items

Item ID	Inventory Item Name	Code
I.1	Tunnel Number	
I.2	Tunnel Name	
I.3	State Code	
I.4	County Code	
I.5	Place Code	
I.6	Highway Agency District	
I.7	Route Number	
I.8	Route Direction	
I.9	Route Type	
I.10	Facility Carried	
I.11	LRS Route ID	
I.12	LRS Mile Point	
I.13	Tunnel Portal's Latitude	
I.14	Tunnel Portal's Longitude	
I.15	Border Tunnel State or Country Code	
I.16	Border Tunnel Financial Responsibility	
I.17	Border Tunnel Number	
I.18	Border Tunnel Inspection Responsibility	

Age and Service Items

Item ID	Inventory Item Name	Code
A.1	Year Built	
A.2	Year Rehabilitated	
A.3	Total Number of Lanes	
A.4	Average Daily Traffic	
A.5	Average Daily Truck Traffic	
A.6	Year of Average Daily Traffic	
A.7	Detour Length	
A.8	Service in Tunnel	

Classification Items

Item ID	Inventory Item Name	Code
C.1	Owner	
C.2	Operator	
C.3	Direction of Traffic	
C.4	Toll	
C.5	NHS Designation	
C.6	STRAHNET Designation	
C.7	Functional Classification	
C.8	Urban Code	

Geometric Data Items

Item ID	Inventory Item Name	Code
G.1	Tunnel Length	
G.2	Minimum Vertical Clearance over Tunnel Roadway	
G.3	Roadway Width, Curb-to-Curb	
G.4	Left Sidewalk Width	
G.5	Right Sidewalk Width	

Load Rating and Posting Items

Item ID	Inventory Item Name	Code
L.10	Height Restriction	
L.11	Hazardous Material Restriction	
L.12	Other Restrictions	

Navigation Items

Item ID	Inventory Item Name	Code
N.1	Under Navigable Waterway	
N.2	Navigable Waterway Clearance	

Structure Type and Material Items

Item ID	Inventory Item Name	Code
S.1	Number of Bores	
S.2	Tunnel Shape	
S.3	Portal Shapes	
S.4	Ground Conditions	
S.5	Complex	

4.12.2 **Sample Inspection Form**

Initial and routine inspections evaluate the condition states of structural, civil, and functional systems. Structural elements are liners, roof girders, columns/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. Civil elements include wearing surfaces, traffic barriers, and pedestrian railings. Functional systems include the mechanical, electrical and lighting, fire and life safety and security, signs, and protective systems.

Forms should be easy to understand and organized for easy database entry. The forms should be supplemented with photographs and sketches to clearly show the deficiency and other useful information. Supplementary notes from the inspection can be kept in a field book or entered electronically.

Data can be collected by hand using pre-printed forms or directly entered electronically using a tablet, personal computer, or other device. Data collected by hand will later need to be entered into the electronic database. Table 4.6 contains a sample element level inspection form that is compatible with the requirements contained in the SNTI.

Direct electronic entry has the advantage of potential time savings, a mechanism for review of historical data for comparison, automatic error checking, and improved accuracy. The inspection team may assign one individual to enter all field data collected directly into the tablet or personal computer during the inspection.

Table 4.6 – Sample tunnel element collection form for initial and routine inspections

National Tunnel Inventory – Inventory and Element Data

Inventory Data
Identification Items

Item ID	Inventory Item Name	Code
I.1	Tunnel Number	
I.2	Tunnel Name	
I.3	State Code	
I.4	County Code	
I.5	Place Code	
I.6	Highway Agency District	
I.7	Route Number	
I.8	Route Direction	
I.9	Route Type	
I.10	Facility Carried	
I.11	LRS Route ID	
I.12	LRS Mile Point	
I.13	Tunnel Portal's Latitude	
I.14	Tunnel Portal's Longitude	
I.15	Border Tunnel State or Country Code	
I.16	Border Tunnel Financial Responsibility	
I.17	Border Tunnel Number	
I.18	Border Tunnel Inspection Responsibility	

Age and Service Items

Item ID	Inventory Item Name	Code
A.1	Year Built	
A.2	Year Rehabilitated	
A.3	Total Number of Lanes	
A.4	Average Daily Traffic	
A.5	Average Daily Truck Traffic	
A.6	Year of Average Daily Traffic	
A.7	Detour Length	
A.8	Service in Tunnel	

Classification Items

Item ID	Inventory Item Name	Code
C.1	Owner	
C.2	Operator	
C.3	Direction of Traffic	
C.4	Toll	
C.5	NHS Designation	
C.6	STRAHNET Designation	
C.7	Functional Classification	
C.8	Urban Code	

Geometric Data Items

Item ID	Inventory Item Name	Code
G.1	Tunnel Length	
G.2	Minimum Vertical Clearance over Tunnel Roadway	
G.3	Roadway Width, Curb-to-Curb	
G.4	Left Sidewalk Width	
G.5	Right Sidewalk Width	

Inspection items

Item ID	Inventory Item Name	Code
D.1	Routine Inspection Target Date	
D.2	Actual Routine Inspection Date	
D.3	Routine Inspection Interval	
D.4	In-Depth Inspection	
D.5	Damage Inspection	
D.6	Special Inspection	

Load Rating and Posting Items

Item ID	Inventory Item Name	Code
L.1	Load Rating Method	
L.2	Inventory Load Rating Factor	
L.3	Operating Load Rating Factor	
L.4	Tunnel Load Posting Status	
L.5	Posting Load – Gross	
L.6	Posting Load – Axle	
L.7	Posting Load – Type 3	
L.8	Posting Load – Type 3S2	
L.9	Posting Load – Type 3-3	
L.10	Height Restriction	
L.11	Hazardous Material Restriction	
L.12	Other Restrictions	

Navigation Items

Item ID	Inventory Item Name	Code
N.1	Under Navigable Waterway	
N.2	Navigable Waterway Clearance	
N.3	Tunnel or Portal Island Protection from Navigation	

Structure Type and Material Items

Item ID	Inventory Item Name	Code
S.1	Number of Bores	
S.2	Tunnel Shape	
S.3	Portal Shapes	
S.4	Ground Conditions	
S.5	Complex	

National Tunnel Inventory – Inventory and Element Data

Element Data

Structural Elements

Element Name	Element Number	Element Parent Number	Total Quantity	Condition State 1 Quantity	Condition State 2 Quantity	Condition State 3 Quantity	Condition State 4 Quantity

Joints & Gaskets

Element Name	Element Number	Element Parent Number	Total Quantity	Condition State 1 Quantity	Condition State 2 Quantity	Condition State 3 Quantity	Condition State 4 Quantity

Civil Elements

Element Name	Element Number	Element Parent Number	Total Quantity	Condition State 1 Quantity	Condition State 2 Quantity	Condition State 3 Quantity	Condition State 4 Quantity

Mechanical System Elements

Element Name	Element Number	Element Parent Number	Total Quantity	Condition State 1 Quantity	Condition State 2 Quantity	Condition State 3 Quantity	Condition State 4 Quantity

Electrical System Elements

Element Name	Element Number	Element Parent Number	Total Quantity	Condition State 1 Quantity	Condition State 2 Quantity	Condition State 3 Quantity	Condition State 4 Quantity

Fire/Life Safety/Security System Elements

Element Name	Element Number	Element Parent Number	Total Quantity	Condition State 1 Quantity	Condition State 2 Quantity	Condition State 3 Quantity	Condition State 4 Quantity

Sign Elements

Element Name	Element Number	Element Parent Number	Total Quantity	Condition State 1 Quantity	Condition State 2 Quantity	Condition State 3 Quantity	Condition State 4 Quantity

Protective Systems Elements

Element Name	Element Number	Element Parent Number	Total Quantity	Condition State 1 Quantity	Condition State 2 Quantity	Condition State 3 Quantity	Condition State 4 Quantity

4.12.2.1 **Sketches**

The documentation of severe defects in any element should contain a sketch showing the pertinent details and a written description of the defect. Each defect should show its length, width, and depth, as well as other information to describe it fully. Label the sketch and provide legends necessary to define abbreviations or terms. For instance, the following scheme can be used to label structural defects:

Description of Defect	Classification
Crack - CR	1 - Minor
Scaling - SC	2 - Moderate
Spall - SP	3 - Severe
Staining - ST	
Exposed Reinforcement - E	
Corrosion - C	
Honeycomb - H	
Patch Failure - PF	
Hollow Area - HA	
Debris - D	
Buckle - B	
Efflorescence - EF	
Leakage - LK	
Check - CK	
Rot - RT	
Fire Damage - FD	
Paint Deterioration – PD	

4.12.2.2 **Photographs**

Photographs provide additional information that may be useful for evaluation by specialists, for quality control, and to establish a historical record. Photographs should be taken for both major defects and typical conditions. A list of photographs taken during the inspection should be recorded on a photo log. Electronic photos are typically assigned a number by the device. Accompanying descriptions should include as much detail as possible. It is helpful to take photographs of the same conditions or defects noted from previous inspections so that the rate of deterioration or effectiveness of repair can be monitored.

4.12.2.3 **Field Record**

Inspection and repair notes to document the inspection should be taken in the field and maintained either electronically or in a bound field book. Information to be recorded and maintained includes notes on safety issues and on discussions with contractors, operations personnel, and other interested parties. Entries should be chronological by date and time, consist of clear, concise, and accurate descriptions of events and contain appropriate sketches. Other information to record and maintain includes: names of inspectors, temperature, weather conditions, and locations that were inspected. These records should be stored electronically.

4.12.2.4 **Inspection Reports**

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

Following are examples of elements in an inspection report:

- **Critical Finding**
  Critical finding refers to defects that require "immediate" action including possible closure of the tunnel where safety or structural concerns are identified using criteria established in the NTIS. Upon discovering a critical finding, the team leader should immediately notify the program manager and the tunnel owner. A brief summary of these details can be included in the inspection report as necessary.

- **Priority Repair**
  Priority repair refers to 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 will reduce future maintenance costs. Elements that do not comply with code requirements are also priorities for repair.

- **Routine Repair**
  Routing repair refers to conditions requiring further investigation or remedial work. This work can be undertaken as part of a scheduled maintenance program, scheduled project, or routine facility maintenance. Items identified in the preventive maintenance program can be put in this category.

Below is a suggested outline for an inspection report and a description of each section:

- **Letter of Transmittal –** Formal identification of report and introduction to the recipient.

- **Table of Contents –** This provides information to the reader on where to find information of a particular interest.

- **List of Tables –** Used to identify the title and location of any tables that were used.

- **List of Figures, Drawings, and Sketches –** Used to identify the title and location of any figures or drawings.

- **List of Photographs –** Used to identify the title and location of any photographs. These may be included as an appendix to the report.

- **Executive Summary –** Provides a concise summary of the inspection, findings, and recommended repairs.

- **General Description –** Provides a general description of the tunnel or tunnels that were inspected. This information could include the location of the tunnel(s), age, general geometry, and any other pertinent descriptive information.

- **General System Descriptions** – Provide general descriptions of the structural, civil, and functional systems inspected and the scope of the elements covered by the inspection. This should precede the detailed descriptions for the inspection findings of each element.

- **Inspection Procedures –** The procedures used to inspect the tunnel elements should be explained and illustrated. If extensive written procedures were followed, these may be included as an appendix to the report. Documentation of any specialized testing processes and outside expertise should be included.

- **Inspection Findings –** The condition of all tunnel elements should be documented using the Condition States CS1, CS2, CS3, and CS4 per the instructions and guidelines in the SNTI.

- **Inspection Results –** A detailed description of the results of the inspection should be included for the various tunnel elements below.

    - <u>Structural and Civil</u> – For structural and civil elements, 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.

    - <u>Mechanical</u> – For the 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.

    - <u>Electrical</u> – For the 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 level measured to recommended levels should be provided to the owner. Remediation work that may accompany testing and inspection should be included.

- **Recommendations –** This section includes recommendations for repair or rehabilitation of the tunnel components found to be deficient or to not meet current code requirements. Substantial rehabilitation may require a life-cycle cost comparison of repair options. Repair and rehabilitation recommendations should be broken down for each of the main tunnel systems into the categories previously described, critical finding, priority repair and routine repair.

- **Appendices –** The appendices can be used for detailed and extensive inspection summaries that are lengthy, highly technical and detailed (such as structural panel ratings and lighting illuminance levels), and reports from special testing agencies. Detailed information such as special permits, processes or qualifications can go in an appendix. An example of this would be a confined space entry permit. A summary of the inspection operation should be provided with a list of inspection personnel, identification of the team leader, the inspection tools used, the access equipment required, and the schedule maintained. This information is useful for planning future inspections as well as for documenting the inspection.

4.13 Glossary of Selected Items

AASHTO	-	American Association of State Highway and Transportation Officials
AC	-	Alternating Current
ATSSA	-	American Traffic Safety Services Association
CCTV	-	Closed Circuit Television
Chord	-	A line segment that joins two points on a curve
CO	-	Carbon Monoxide
DC	-	Direct Current
ETS	-	Emergency Trip Switch
FHWA	-	Federal Highway Administration
Gunite	-	Term commonly used for fine-aggregate shotcrete
gpm	-	Gallons per minute
IES LM-50	-	Illuminating Engineering Society, Lighting Measurements – 50
IES RP-22	-	Illuminating Engineering Society, Recommended Practices – 22
ITE	-	Institute of Transportation Engineers
Km/h	-	Kilometers per hour

mph	-	Miles per hour
MTS	-	Maintenance Testing Specifications
MUTCD	-	Manual on Uniform Traffic Control Devices
NATM	-	New Austrian Tunneling Method (synonymous with SEM)
NBIS	-	National Bridge Inspection Standards
NBS	-	National Bureau of Standards
NEMA	-	National Electric Manufacturers Association
NETA	-	National Electrical Testing Association
NFPA	-	National Fire Protection Association
OSHA	-	Occupational Safety and Health Administration
PEI	-	Porcelain Enamel Institute
SEM	-	Sequential Excavation Method (synonymous with NATM)
TBM	-	Tunnel Boring Machine
TSS	-	Track Safety Standards
UPS	-	Uninterruptible Power Supply

References

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TOMIE MANUAL

CHAPTER 5

EVALUATION

Chapter 5 - Evaluation

5 Evaluation

The cost of maintaining and improving tunnel systems must be balanced against the amount of available funding. Resources are limited for making 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 disposing of tunnel system components in a cost-effective manner.

When a structural system within the tunnel supports vehicular live loads, a load rating must be performed in accordance with the National Tunnel Inspection Standards (NTIS). The results of the load rating may be used to determine the need for a load posting, or the rating may be used to issue a hauling permit.

This chapter focuses on the evaluation of tunnel systems and components to include the typical personnel involved, supplemental inspection and testing methods, risk-based assessments, priority classification, and basic cost estimating. Information is also provided on load rating.

5.1 Qualifications of Personnel

The program manager and team leader should be included in the evaluation team. If the tunnel systems are complex, it may be advisable to use qualified specialists, specialty contractors, or consultants to augment the evaluation process. The evaluation team should have a thorough understanding of the tunnel facility including operations, maintenance, inspection, design, cost estimating, scheduling, construction, and rehabilitation.

The tunnel owner should establish the qualifications necessary for evaluating various tunnel systems and components to include criteria for education, training, experience, and certification or professional registration. The qualifications of the evaluation team should commensurate with the written policies and procedures for tunnel inspection. In accordance with the NTIS, *the load rating of a tunnel must be performed by a professional engineer*. A professional engineer is typically characterized as an individual who has fulfilled specific education and experience requirements and passed certain examinations that permit the person to provide appropriate engineering services within a jurisdiction in accordance with all applicable laws.

5.2 Supplemental Inspections and Testing

Sometimes additional information is needed after an inspection to complete an evaluation; or additional data may be needed to further define a particular deficiency, the sectional properties of an element, or the engineering properties of a material. In-depth and special inspections, as defined in Chapter 4 of this manual, are often used to obtain additional information during the evaluation process. There are also several field test and laboratory techniques for evaluating material properties.

5.2.1 **Nondestructive Test Methods**

NDT methods are useful for a variety of purposes ranging from verifying the tunnel geometry to identify temperature differences. Additional nondestructive testing (NDT) methods generally used with tunnels include:

- Air-coupled GPR
- Infrared thermography
- Scanners
- Ground-coupled GPR
- Ultrasonic tomography
- Ultrasonic echo
- Ultrasonic surface waves
- Impact echo

Information on non-destructive testing can be found at:

http://www.ndtoolbox.org/content/tunnels

The limitations of these technologies should be considered prior to implementing them. The techniques typically produce reasonable results when the defects are at least 1 square foot and located at depths less than 4 inches below the surface.

NDT technologies are used to better characterize the extent of deficiencies in structural elements below the surface. Baseline readings should be obtained on critical elements to monitor defects and rate of decline. NDT methods generally require specialized and proprietary equipment purchased from a vendor. With respect to highway tunnel applications, various NDT methods can be used to evaluate:

- Water leakage.
- Delamination and spalling of concrete liners.
- Voids behind and within tunnel linings.
- Concrete permeability.
- Tiles that are in the process of separating from the tunnel liner.
- Integrity of concrete covered steel liners.
- Integrity of ceiling systems and connections with the tunnel lining.

5.2.2 **Field Test Methods**

The AASHTO Manual for Bridge Evaluation (MBE) discusses various field tests for concrete, steel, and timber. The field tests for concrete include strength methods, sonic methods, ultrasonic techniques, magnetic methods, electrical methods, nuclear methods, thermography, radar, radiography, and endoscopes. The field tests for steel include radiography, magnetic particle examination, eddy current examination, dye penetrant examination, and ultrasonic examination. The field tests for timber include penetration methods, electrical methods, and ultrasonic examination. In addition, it may be necessary to perform field tests on the geological and geotechnical materials in the vicinity of the tunnel. Some of the common ASTM field test methods for rock and soil are listed in Tables 5.1 and 5.2.

Table 5.1 – Field Tests for Geological (Rock) Materials

Test Designation	Title of Test
ASTM D 4435	Method for Rock Bolt Anchor Pull Test
ASTM D 4436	Method for Rock Bolt Long-Term Load Retention Test
ASTM D 4553	Method for Determining In Situ Creep Characteristics of Rock
ASTM D 4554	Method for In Situ Determination of Direct Shear Strength of Rock Discontinuities
ASTM D 4623	Method for Determination of In Situ Stress in Rock Mass by Overcoring Method—USBM Borehole Deformation Gauge
ASTM D 4729	Method for In Situ Stress and Modulus of Deformation Using Flatjack Method

Table 5.2 – Field Tests for Geotechnical (Soil) Materials

Test Designation	Title of Test
ASTM D 2573	Method for Field Vane Shear Test in Cohesive Soil
ASTM D 4044	Method for (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers
ASTM D4050	Method for (Field Procedure) for Withdrawal and Injection Well Testing for Determining Hydraulic Properties of Aquifer Systems

5.2.3 **Laboratory Test Methods**

The MBE discusses various laboratory tests methods for concrete, steel, and timber. Table 5.3 and 5.4 list the ASTM standards that are commonly used for laboratory testing of geological (rock) and geotechnical (soil) materials. Laboratory tests should be conducted by facilities that meet the requirements established in the respective standards.

Table 5.3 – Laboratory Tests for Geological (Rock) Materials

Test Designation[(1)]	**Title of Test**
D2936	Method for Direct Tensile Strength of Intact Rock Core Specimens
D 3967	Method for Splitting Tensile Strength of Intact Rock Core Specimens
D 4535	Methods for Measurement of Thermal Expansion of Rock Using Dilatometer
D 4644	Method for Slake Durability of Shales and Similar Weak Rocks
D 5607	Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force
D 5731	Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications
D 5873	Method for Determination of Rock Hardness by Rebound Hammer Method
D 6032	Method for Determining Rock Quality Designation (RQD) of Rock Core
D 7012	Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures
D 7070	Methods for Creep of Rock Core Under Constant Stress and Temperature
D 7401	Methods for Laboratory Determination of Rock Anchor Capacities by Pull and Drop Tests
D 7625	Method for Laboratory Determination of Abrasiveness of Rock Using the CERCHAR Method

Table 5.4 – Laboratory Tests for Geotechnical (Soil) Materials

Test Designation[(1)]	**Title of Test**
D 422	Method for Particle-Size Analysis of Soils
D 2166	Method for Unconfined Compressive Strength of Cohesive Soil
D 2216	Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D 2435	Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading
D 2850	Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils
D 3080	Method for Direct Shear Test of Soils Under Consolidated Drained Conditions
D 4318	Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
D 4546	Methods for One-Dimensional Swell or Collapse of Soils
D 4648	Method for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil
D 4829	Method for Expansion Index of Soils
D6913	Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis
D 7263	Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens

5.3 Evaluation of Tunnels

Inspection findings are used to determine if there are safety and structural concerns. Tunnel systems provide a certain level of safety and enhance service; the criticality of the component should be evaluated for safety, service, and cost implications. Evaluations are used to prioritize repairs and to make informed investment decisions. A data-driven, risk-based approach can be used to achieve optimized performance. Repair decisions are focused on costs and funding availability; as such, a cost estimate is an important part of the evaluation process. Sound engineering judgment is needed to arrive at meaningful conclusions.

5.3.1 **Evaluation Strategies**

Components of tunnel evaluation strategies include risk assessment, priority classification, cost estimating, life cycle prediction, and asset management. The scope and depth of an evaluation will vary depending on the complexity and sophistication of the tunnel. Tunnel evaluation programs are developed to suit the overall needs of the tunnel owner.

5.3.1.1 **Risk-Assessment**

Risk assessment is intended to provide a cost effective approach to decision-making based on analysis of data. Risks are evaluated using various qualitative or quantitative techniques, and the consequences of component or system failure are considered. Consequences are evaluated for safety, security, service level, and cost. A risk register is a common tool that is used for identifying risks. Evaluation helps to prioritize repairs and optimize resources as part of an effective tunnel management approach.

5.3.1.2 **Priority Classification**

Priority classification is performed as part of the inspection process to ensure that conditions discovered during an inspection get the proper rating. Similarly, evaluations should include a priority classification scheme that supports the management approach. An example priority classifications scheme is described below:

Critical Finding – A defect or deficiency that requires <u>immediate</u> action as defined in the NTIS.

Priority Repair – These repairs will improve the durability, reliability, aesthetics, or functional capability of the tunnel system and will reduce future maintenance costs. Elements that no longer comply with code requirements might also be included in this classification depending on the policies of the tunnel owner. These repairs typically require quality checking to ensure adequate performance and are generally scheduled for repair prior to the next inspection cycle.

Routine Repair – These repairs are part of not as critical to the safety and performance of the tunnel structure and can be repaired when more budget is available or as part of a routine maintenance program. These repairs are typically completed when the schedule permits.

Figure 5.1 depicts an optimized replacement plan for an off-the-shelf pump motor deemed to have minimal consequence of failure. Figure 5.2 depicts an optimized preventative maintenance schedule for a customized fan motor deemed to have a high consequence of failure.

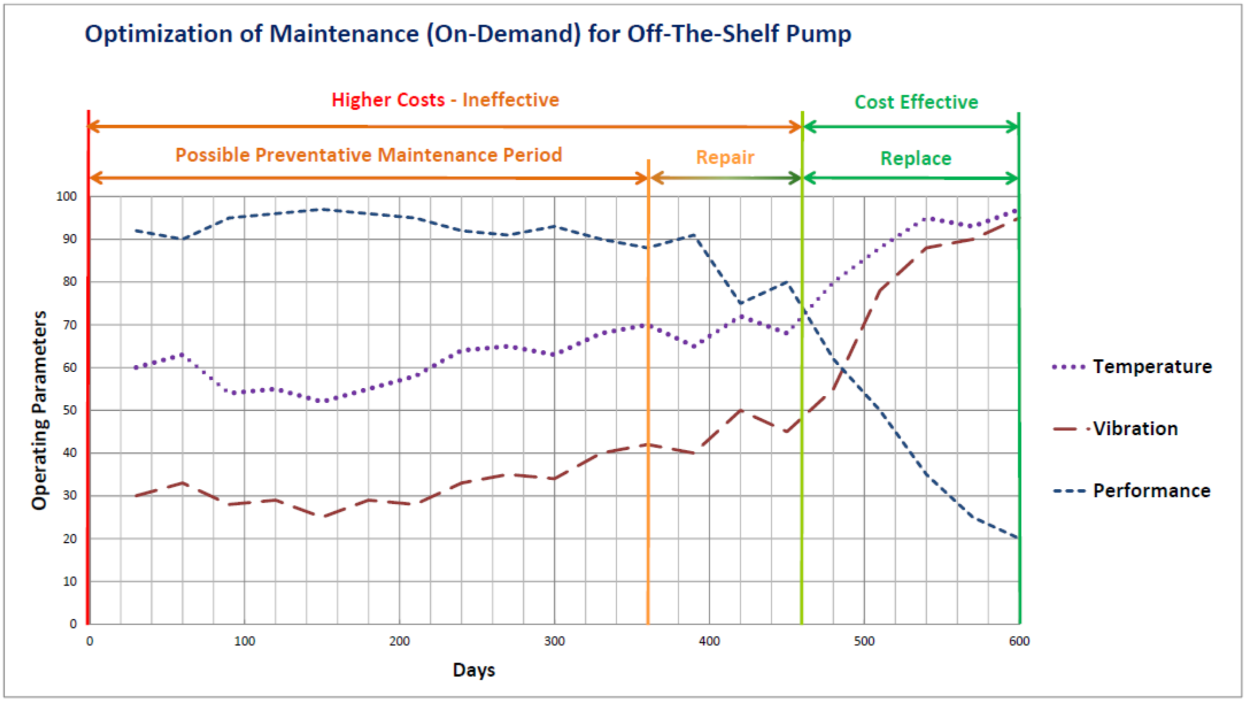

Figure 5.1 – Optimized on-demand maintenance for an off-the-shelf pump.

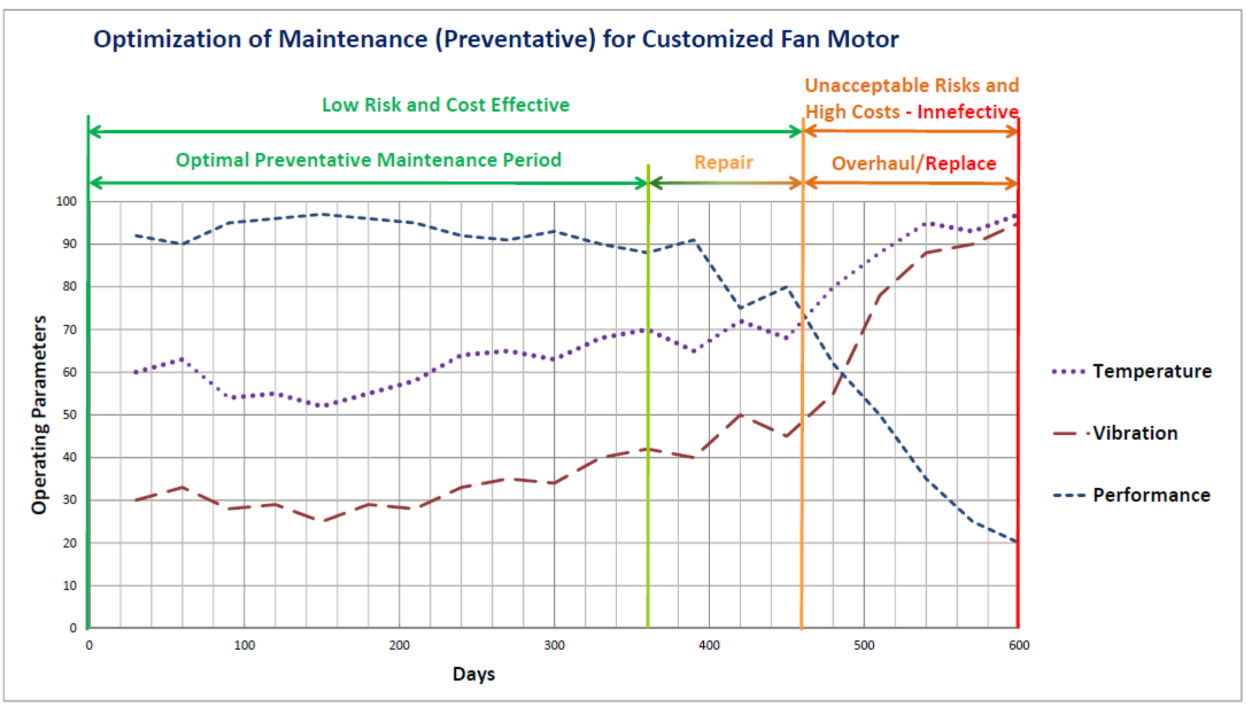

Figure 5.2 – Optimized preventative maintenance schedule for a customized motor.

5.3.1.3 **Cost Estimating**

A cost estimate is usually needed as part of the evaluation process to successfully manage and budget for repairs. Alternative repair schemes also need cost estimates for comparison purposes. Repair costs are influenced by a number of considerations. For evaluation purposes, a sufficient cost estimate can generally be made using methods discussed in AASHTO 2013. This guide identifies four key estimating techniques to include:

- Conceptual estimating
- Bid-based estimating
- Cost-based estimating
- Risk-based estimating

Based on the estimated quantities of labor, materials, and equipment and meaningful consideration of incidental items, such as mobilization of equipment, traffic maintenance, contingency, subcontractor fees, and contractor overhead and profit, sufficient cost estimates can be made for evaluation purposes. If the repair scheme involves work at a future date, then the time value of money must be taken into account.

Table 5.5 shows a very simple example of a cost estimate that compares two different repair schemes where the amount of repair work does not change over the repair period. This simple example indicates that if funds are limited in any particular year, then there is not a significant difference when the repairs are performed. In other cases, the cost and amount of repair work could significantly increase because of inflation and the neglected repairs could increase the rate of deterioration and require more extensive repairs.

5.3.1.4 **Life-Cycle Costs**

Life cycles are estimated using relevant deterioration models based on data collected over many inspection cycles. Cost effective strategies consider the costs of various competing alternatives over a specific duration or time period such as the remaining useful life of a particular tunnel system, the next ten years, etc. Life-cycle analysis is a useful tool for evaluating capital investment alternatives such as whether to purchase, own, operate, maintain, or replace an asset. For example when considering obsolete fan systems, it might require less up-front capital to overhaul the motors than purchase new motors; however, the new fan motors may last longer, consume less power, and require less maintenance expenditures, which over the useful life cycle could cost less. If the new controllers are compatible with the planned supervisory control and data acquisition system, then these benefits should also be included in the evaluation.

5.3.1.5 **Asset Management**

Asset management involves deploying, operating, maintaining, upgrading, and replacing tunnel system components in a cost-efficient manner while maintaining acceptable levels of safety and service. These schemes evaluate alternatives and determine the most effective use of limited resources by employing optimized allocation techniques.

Table 5.5 – Sample simple cost estimate for comparing two alternative repair schemes.

Item		Repair	Labor		Material		Equipment		Costs	
			Quantity	Unit Cost	Quantity	Unit Cost	Quantity	Unit Cost	Time Value of Money i=6%	Dollars
			Hours	$/Hour	yd^3 (Cubic Yards)	$\$/yd^3$	Days	$/Day		
ALT 1	**Year 1**	Voids	60	55.00	300	175.00	8	500.00	-	59,800
		Cracks	20	25.00	10	75.00	3	50.00	-	1,400
		Etc.	-	-	-	-	-	-	-	
		Total								61,200 + …
	Year 3	Voids	10	55.00	50	175.00	2	500.00	1,275	11,575
		Cracks	5	25.00	3	75.00	1	50.00	50	450
		Etc.	-	-	-	-	-	-	N x 1.06^2	
		Total								12,025 + …
	Total									73,225
ALT 2	**Year 1**	Voids	30	55.00	150	175.00	4	500.00	-	29,900
		Cracks	10	25.00	5	75.00	2	50.00	-	725
		Etc.	-	-	-	-	-	-	-	
		Total								30,625 + …
	Year 3	Voids	40	55.00	200	175.00	5	500.00	4,900	44,605
		Cracks	15	25.00	8	75.00	2	50.00	135	1,210
		Etc.	-	-	-	-	-	-	N x 1.06^2	
		Total								45,815 + …
	Total									76,440

5.3.2 Civil and Structural Evaluations

When establishing the conditions of the tunnel and evaluating the engineering properties of the materials, it is important to have the existing records available to obtain the appropriate design, construction, and maintenance information. The geotechnical records should also be reviewed to obtain the soil parameters and the groundwater information. This information may be useful for example when assessing a leaking segment of the tunnel or where the geometry of the tunnel cross-section changes. If any essential information is missing, special or in-depth inspections can be used to obtain the missing information.

Table 5.6 – Sample simple ranking for repair of a civil or structural component.

Ranking	Repair	Structure Condition	Risk	Priority	Costs		Effectiveness		Remarks
					Alt 1	Alt2	Alt 1	Alt2	
1	Replace Ceiling Slab and Girders	Severe	High	Priority	1,750,000	2,250,000	+$750,000	+$0	Plenum ice => overload. Now temp supported
2	Patch Interior Wall and Tile	Poor	Moderate	Routine	$50,000	$75,000	+$40,000	+$5,000	Concrete spalls + tile observed on roadway
…..	…..	…..	…..	…..		…..		…..	..

A table can be set up as a tool for evaluating civil and structural elements based on the basic evaluation schemes that were previously discussed. From Table 5.6 for example, qualitative evaluations can be used to rank repairs. The evaluation method developed should be based on the policies and practices of the tunnel owner. More elaborate quantitative methods can be developed to take advantage of multi-variable codified input parameters using sophisticated algorithms processed by computer software; however, it is highly recommended to use engineering judgment as a final check for evaluating quantitative results.

Structural Analysis – It is important to evaluate the changes that might impact the load carrying capacity and durability of civil and structural elements. The primary considerations include material degradation and section loss. Loads may have changed over time due to a number of factors such as the installation of new equipment, heavier truck use, earthwork, and changing groundwater levels. The evaluation should consider the pertinent assumptions used in the design to include any standards, codes, or criteria that were used. A structural analysis should be performed on a structure that supports loads in the tunnel when there are changes to:

- The loads supported by the tunnel structure.
- Section loss occurs in the structure.
- The material properties are degraded due to corrosion and deterioration.

The ground interacts with the tunnel liner rather than simply acting as an applied load on the final liner. The ground should be treated as a material with engineering properties to include strength, stiffness, and weight. The ground may also distribute all or a portion of the live loads in the vicinity of the tunnel. If a highway tunnel supports live loads from aircraft or rail vehicles, it would be prudent to conduct a structural analysis of the tunnel liner.

5.3.3 Evaluation of Functional Systems

Functional systems are comprised of various components that provide essential services such as ventilation, pumping, flood protection, heating, cooling, distribution of power, emergency power generation, lighting, fire detection, fire protection, communication, and surveillance. When evaluating functional systems, it is also important to obtain the design, construction, and maintenance records to establish the configuration and as-built conditions of the functional system components. Schematics, diagrams, and schedules provide important information about the interworking of these systems; the evaluation team should understand them; and it is common to employ qualified specialists, specialty contractors, and consultants when evaluating functional systems.

Functional systems can be complex with interdependent components that are shared between different tunnel systems. Some components may be redundant, and complete failure of one item may not prevent the system as a whole from functioning as intended. Other components may lack redundancy, and their failure could result in partial or total system failure. It is also important to review the standards, codes, and the criteria that are referenced in the project records.

A table can be helpful for evaluating functional systems. For example, Table 5.7 presents a simple ranking scheme that may be useful for making repair decisions. The evaluation method developed should be based on the policies and practices of the tunnel owner. More elaborate quantitative methods should be developed, as needed, to take advantage of more sophisticated computer algorithms if they are available; however, it is highly recommended that engineering judgment be used to evaluate all of the results.

Table 5.7 – Example of a simple ranking for repair or replacement of a functional system.

Ranking	Repair	Structure Condition	Risk	Priority	Costs		Effectiveness		Remarks
					Alt 1	Alt2	Alt 1	Alt2	
1	Replace Ceiling Slab and Girders	Severe	High	Priority	1,750,000	2,250,000	+$750,000	+$0	Plenum ice => overload. Now temp supported
2	Patch Interior Wall and Tile	Poor	Moderate	Routine	$50,000	$75,000	+$40,000	+$5,000	Concrete spalls + tile observed on roadway
…..	…..	…..	…..	…..		…..		…..	..

5.3.3.1 Mechanical systems

Mechanical systems include the fan and ventilation system, drainage system and pumps, the emergency generator, flood gates, and other such components. The requirements for mechanical systems are generally established by State and local authorities that adopt provisions from building codes, standards, or design guides. The requirements for each tunnel should be established in the file records. If the file records indicate that, for example, a particular mechanical system was designed to meet the requirements of the International Mechanical Code of the International Code Council (2015 Edition) or the Unified Plumbing Code of International Association of Plumbing and Mechanical Officials (2012 Edition), then these references serve as a basis for establishing the minimum requirements for the mechanical components, as applicable.

Figures 5.3 through 5.5 illustrate the type of information that should be understood when evaluating functional systems such as flow diagrams, fan schedules, and wiring diagrams. When evaluating components of mechanical system, the effects of an element on the system as a whole must be understood. For example:

- Is the component redundant within the system?
- Is the component only for boosting normal operating capacity during peak travel?
- Is the component needed for mitigating emergency conditions?
- Is the component needed to satisfy the required redundancy levels?

Ventilation system – The ventilation system dilutes vehicle fumes and exchanges the air during normal operations; during fires, these systems are used to control the smoke, pressurize escape routes, and exhaust dangerous fumes and superheated gasses from the tunnel. Ventilation systems may include the following subcomponents: fans, airways, sound attenuators, dampers, damper motor, damper controller, air quality monitoring equipment such as for carbon monoxide (CO), control panels and conduit.

Drainage and pumping system – These elements may include storm drains, piping, pumps and water treatment equipment. The drainage and pumping system may include various subcomponents such as motors and controllers.

Emergency generator system – The elements of this system include the mechanical components of the emergency generator such as fuel delivery pumps, fuel storage, engine components, engine cooling system, and exhaust components. The emergency generator system may include the following subcomponents: main fuel storage tank, day fuel tanks, circulating fuel pumps, fuel tank ventilation, fuel tank sensors, cooling systems, exhaust manifold, insulation, exhaust air louver and damper actuator, supply air louver and damper actuator, generator, generator control equipment, control panels, and associated conduit.

Flood gates – Flood gates generally include seals, mechanical components, hydraulic systems, and power supply equipment.

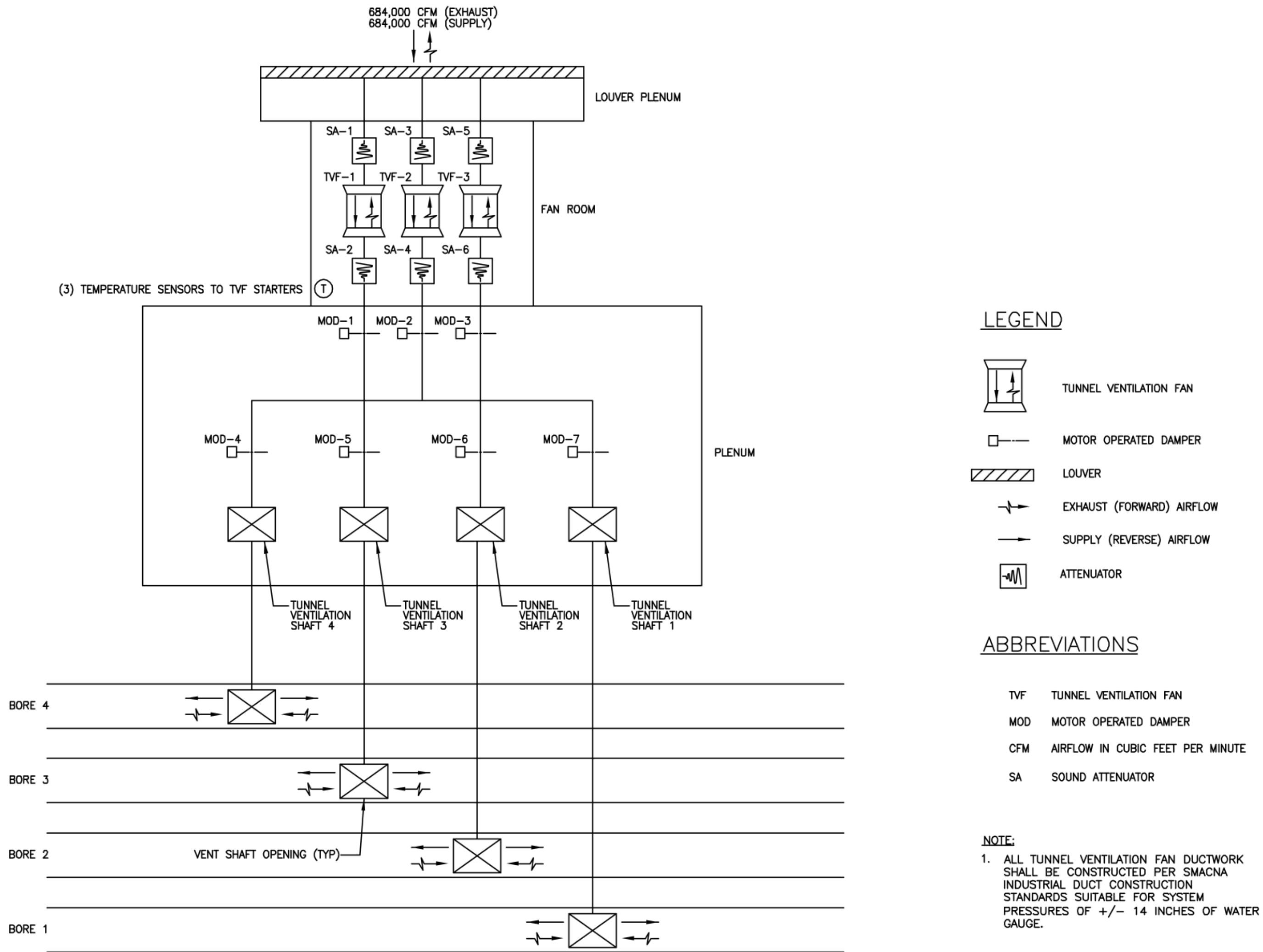

Figure 5.3 – Sample tunnel ventilation air flow diagram.

TUNNEL VENTILATION FAN SCHEDULE

FAN NO.	LOCATION	FAN DATA: AIR QUANTITY (CFM)	FAN DATA: TOTAL PRESS. (IN. W.G.)	FAN DATA: NOMINAL FAN DIA. (INCHES)	FAN MOTOR DATA: MAXIMUM NAMEPLATE HP	FAN MOTOR DATA: RPM	FAN MOTOR DATA: VOLTS	FAN MOTOR DATA: PHASE	FAN MOTOR DATA: HERTZ	MAXIMUM FAN SOUND POWER LEVELS (dB re 10^{-12} WATTS): 63 HZ	125 HZ	250 HZ	500 HZ	1K HZ	2K HZ	4K HZ	8K HZ	REMARKS
TVF–1	FAN ROOM	228,000	5.60	96	350	1,200/600	460	3	60	111	116	126	129	125	121	117	114	SEE NOTES 1, 2 AND 3.
TVF–2	FAN ROOM	228,000	5.60	96	350	1,200/600	460	3	60	111	116	126	129	125	121	117	114	SEE NOTES 1, 2 AND 3.
TVF–3	FAN ROOM	228,000	5.60	96	350	1,200/600	460	3	60	111	116	126	129	125	121	117	114	SEE NOTES 1, 2 AND 3.

NOTES:

1. THE INDICATED AIRFLOW CAPACITY AND TOTAL PRESSURE REQUIREMENTS FOR TUNNEL VENTILATION FANS APPLY TO FAN OPERATION IN FORWARD (EXHAUST) MODE. THE REQUIRED AIRFLOW CAPACITY AND TOTAL PRESSURE FOR REVERSE (SUPPLY) MODE IS 228,000 CFM AT 5.40 IN. W.G.
2. FAN PERFORMANCE DATA INDICATED IS BASED ON AIR DENSITY OF 0.085 POUNDS PER CUBIC FOOT.
3. MOTOR HORSEPOWER SHALL NOT EXCEED 350.
4. SEE NOTES 3 TO 5 OF ATTENUATOR SCHEDULE.

TUNNEL VENTILATION MOTOR OPERATED DAMPER SCHEDULE

DAMPER NO.	LOCATION	FRAME MOUNTING PLANE	CLEAR OPENING INSIDE DAMPER (FT–IN.): "A"	CLEAR OPENING INSIDE DAMPER (FT–IN.): "B"	NUMBER OF EQUAL MODULES	DAMPER MOTOR OPERATOR – MOTOR DATA: MAX. HP	VOLTS	PHASE	HERTZ	MIN. NO. OF MOTOR OPERATORS	DE–ENERGIZED DAMPER POSITION	MOTOR LOCATION: IN AIR STREAM	MOTOR LOCATION: SIDE–MOUNTED	REMARKS
MOD–1	FAN PLENUM	VERTICAL	10'–0"	12'–0"	2	1/3	120	1	60	2	OPEN	X	–	SEE NOTE 1.
MOD–2	FAN PLENUM	VERTICAL	10'–0"	12'–0"	2	1/3	120	1	60	2	OPEN	X	–	SEE NOTE 1.
MOD–3	FAN PLENUM	VERTICAL	10'–0"	12'–0"	2	1/3	120	1	60	2	OPEN	X	–	SEE NOTE 1.
MOD–4	FAN PLENUM	HORIZONTAL	16'–0"	18'–0"	8	1/3	120	1	60	4	OPEN	X	–	SEE NOTE 1.
MOD–5	FAN PLENUM	HORIZONTAL	16'–0"	18'–0"	8	1/3	120	1	60	4	OPEN	X	–	SEE NOTE 1.
MOD–6	FAN PLENUM	HORIZONTAL	16'–0"	18'–0"	8	1/3	120	1	60	4	OPEN	X	–	SEE NOTE 1.
MOD–7	FAN PLENUM	HORIZONTAL	16'–0"	18'–0"	8	1/3	120	1	60	4	OPEN	X	–	SEE NOTE 1.

NOTE:

1. DAMPER ACTUATORS SHALL BE OF THE ALL–ELECTRIC TYPE ONLY. ELECTROHYDRAU TYPE ACTUATORS ARE UNACCEPTABLE.

FAN SOUND ATTENUATOR SCHEDULE

SILENCER NO.	FAN SERVED	OVERALL DIMENSIONS WxHxL (FEET–INCHES)	AIR QUANTITY (CFM)	FACE VELOCITY (FPM)	MAX. PRESS. DROP(IN. W.G.)	OCTAVE BAND HERTZ (MINIMUM DYNAMIC INSERTION LOSS IN DECIBELS): 63	125	250	500	1K	2K	4K	8K	REMARKS
SA–1	TVF–1	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–2	TVF–1	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–3	TVF–2	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–4	TVF–2	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–5	TVF–3	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–6	TVF–3	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.

NOTES:

1. SIZE AND NUMBER OF MODULES SHALL BE AS REQUIRED TO MEET THE SPECIFIED PERFORMANCE.
2. MINIMUM DYNAMIC INSERTION LOSS VALUES ARE FOR FORWARD FLOW (NOISE AND AIR MOVING IN THE SAME DIRECTION).
3. ATTENUATOR/FAN COMBINED NOISE SHALL BE DEFINED AS THE SPECIFIED FAN NOISE LESS THE SPECIFIED ATTENUATOR DYNAMIC INSERTION LOSS.
4. CONTRACTOR TO ENSURE FAN VENDOR AND ATTENUATOR VENDOR COLLABORATE TO ENSURE THAT THE ATTENUATOR/FAN COMBINED NOISE IS NOT EXCEEDED.
5. CONTRACTOR TO ENSURE FAN VENDOR AND ATTENUATOR VENDOR COLLABORATE DURING FACTORY TESTING. TEST FAN NOISE LEVELS FIRST. ADJUST/MODIFY ATTENUATORS DURING ATTENUATOR TESTS TO ENSURE ATTENUATOR/FAN COMBINED NOISE IS NOT EXCEEDED.

Figure 5.4 – Sample tunnel ventilation fan and sound attenuator schedule.

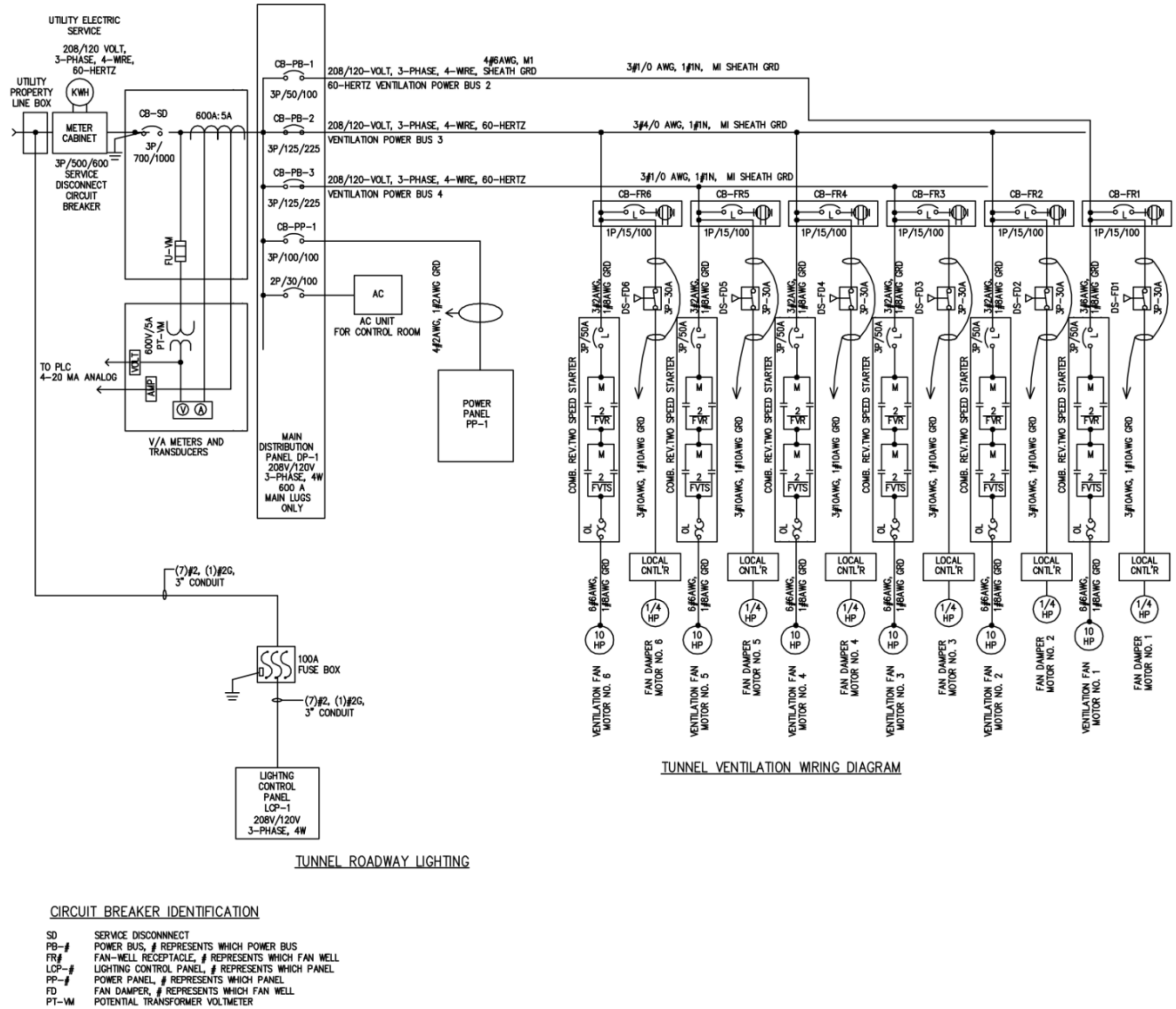

Figure 5.5 – Sample tunnel ventilation and lighting diagram.

5.3.3.2 **Electrical and lighting systems**

The electrical and lighting systems include power distribution system, emergency power distribution system, tunnel lighting and their support fixtures, and emergency lighting and their support fixtures. Figure 5.5 illustrates the type of information that should be understood in the course of evaluating electrical and lighting systems to include various diagrams.

The requirements for electrical and tunnel lighting are usually established by State and local authorities using provisions from building codes, standards, and design guides. The requirements for the electrical and lighting systems should be documented in the file records. If the file records indicate that, for example, the electrical and lighting systems comply with the National Fire Protection Association (NFPA) 70 of the National Electrical Code (2014 Edition) and the American National Standards Institute/Illuminating Engineering Society (ANSI/IES) RP-22 of Tunnel Lighting (2011 Edition), respectively, then these references serve as a basis for establishing the minimum requirements for these systems, as applicable.

Power distribution system – The electrical distribution system consists of the electrical equipment, wiring, conduits, and cables used for distributing electrical energy from the utility supply (service entrance) to the line terminals of utilization equipment. The electrical distribution system may include the following subcomponents: switchgear, unit substations, switchboard, motor control centers, starters, transformers, transfer switches, panel boards, conduits and raceways, and electrical outlets and receptacles.

Emergency power distribution system – This system consists of the electrical equipment, wiring, conduits, and cables used for providing electrical power in case of utility service failure. Equipment included in this system consists of emergency generators and uninterruptible power supply (UPS) systems, transfer switches, and other equipment supplying emergency power. The emergency distribution system may also include the following subcomponents: UPS, batteries, and battery charging equipment. In many tunnels, the UPS limits power supply fluctuations to equipment in the tunnel during normal operations. The mechanical components of the emergency generator are evaluated using techniques for mechanical elements.

Lighting systems – These systems consist of the light fixtures, supports, bulb housings, lenses, light switches, junction boxes, wiring, conduits, cables, sensors, and the controllers. The tunnel lighting system may also include the following subcomponents: photo cell controls and remote ballasts.

Lighting fixtures – Tunnel lighting fixture component supports include anchorage to the supporting member and connecting hardware for the component housing. Fixtures include the physical housing of the lights and their connections to the tunnel structure.

The lights in a tunnel allow the drivers to see objects inside the tunnel and thus serve an important safety function. In the daytime, additional lighting is needed near the entrances to allow time for the driver’s eyes to adjust to the darker conditions within the tunnel while ensuring that the safe stopping-sight-distance is always maintained. Lights are also used during emergencies to illuminate egress routes and provide sufficient light for first responders. When evaluating the effects of several inoperable lights, it is important to consider whether the inoperable lights:

- Are redundant within the lighting system.
- Are only needed for daytime use.
- Are needed for normal tunnel operations.
- Are used for normal operations and during emergency conditions.
- Are connected only to the emergency power distribution system.
- Do not adversely impact the required illumination levels.

Emergency lighting systems and fixtures – These systems consist of the light fixtures, supports, bulb housings, lenses, light switches, junction boxes, wiring, conduits, cables, sensors, and controllers used to provide emergency lighting for the facility. The emergency lighting system may also include the following subcomponents: exit signs, batteries, support space sighting, and remote ballasts.

5.3.3.3 **Fire and life safety systems**

Fire and life safety systems include fire detection systems, fire protection systems, emergency communication systems, and tunnel operation systems. Normally specialists, specialty contractors, or consultants with in-depth knowledge of tunnel operation, emergency response, and technical comprehension of the equipment are needed to evaluate these systems. When evaluating fire and life safety systems, it is important for the tunnel owner to review any significant inspection findings with the fire department that serves the tunnel facility. Figures 5.6 and 5.7 illustrate the type of information that should be understood when evaluating fire and life safety systems. Included in these figures are fire alarm riser and CCTV line diagrams.

The requirements for fire and life safety are usually established by State and local authorities by adopting provisions from building codes, standards, and design guides. The requirements for each tunnel should be documented in the file records or the concept of operations document. If the file records indicate that, for example, the tunnel complies with the National Fire Protection Association (NFPA) 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways (2014 Edition) or portions of the Municipal fire code, then these references serve as a basis for establishing the minimum requirements for the fire and life safety systems, as applicable.

Fire detection system – The fire detection systems consist of control panels, initiating devices (e.g., heat and smoke detectors, pull-stations), notification appliances (e.g., strobes, horns), wiring, conduits, and cables used to detect a fire in the tunnel. The fire detection system may also include the following subcomponents: sensors, controls, and alarms.

Fire protection systems – The fire protection system consists of fire extinguishers, hose connections, storage tanks, fire hydrants, building sprinklers, pumping systems, piping, circulating pumps, and hose reels. The fire protection system may include the following subcomponents: main fire pump, pressure maintenance/jockey pump, dry pipe valve, valves and tamper switches, storage tanks, tunnel stand pipe, pressure relief and air release valves, backflow prevention, hose stations, hose reels, building sprinklers, water heating systems, fire department connections, and fire hydrants.

5.3.3.4 **Tunnel security systems**

Tunnel operations and security systems consists of the 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.

5.3.3.5 **Emergency communications systems**

Emergency communication systems are integral to both fire and life safety systems and tunnel security systems. The components of the emergency communication system include communication devices (e.g., 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. Emergency egress signs offer a relatively low-cost way to improve safety, and the recent studies from AASHTO, FHWA, and the World Road Committee (PIARC) should be considered.

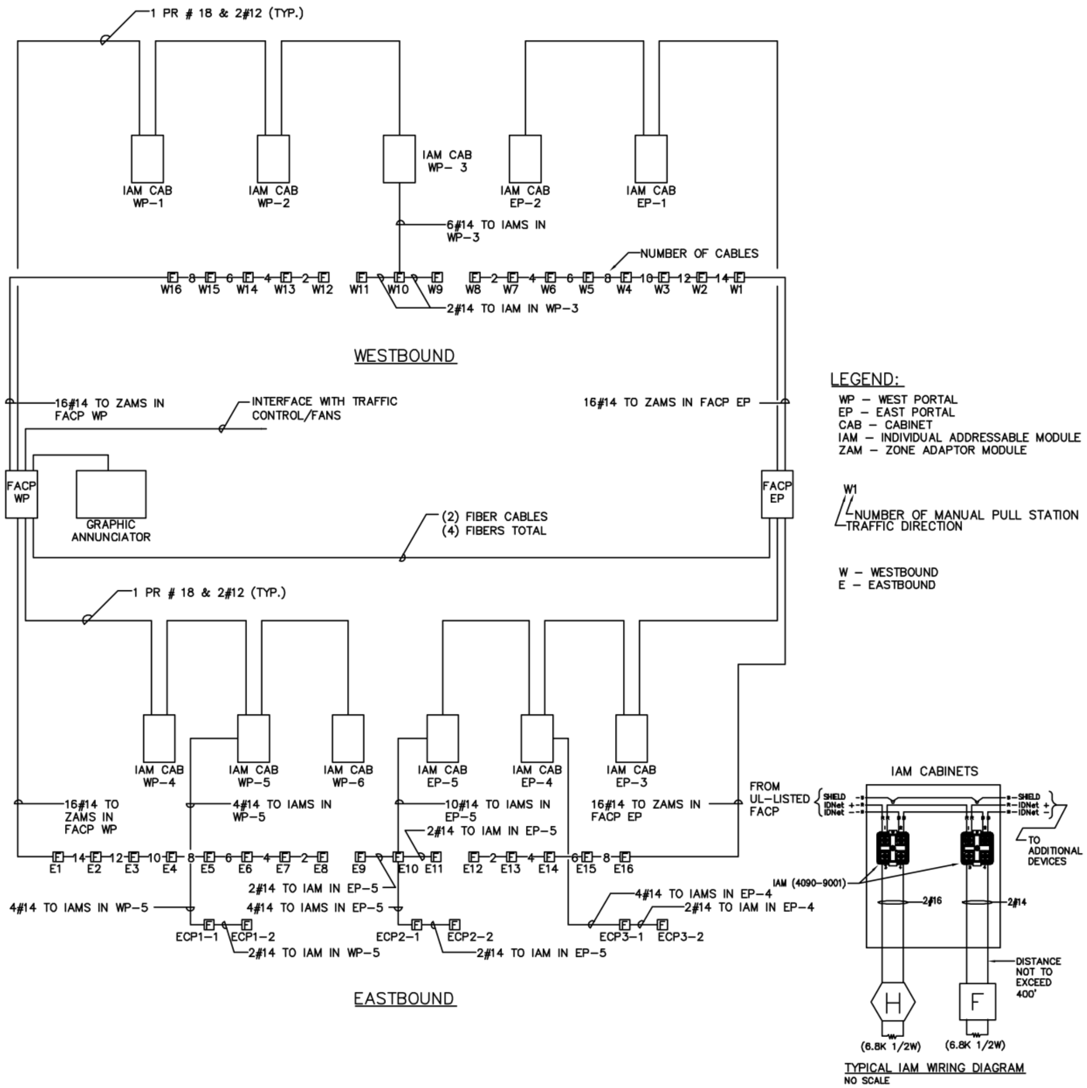

Figure 5.6 – Sample Fire Alarm Riser Diagram.

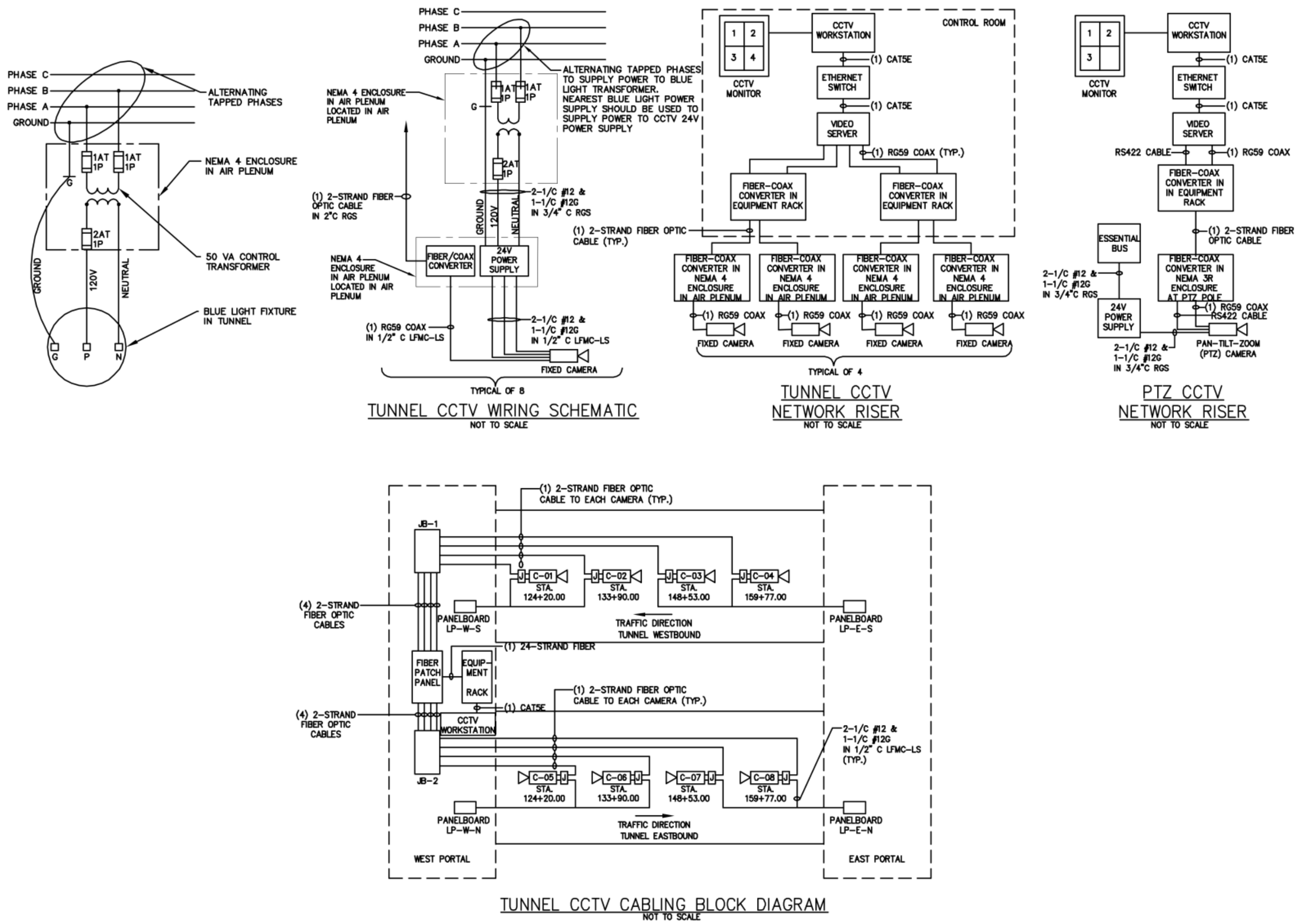

Figure 5.7 – Sample CCTV Line Diagram.

5.3.3.6 **Signs and information systems**

The sign and information systems include traffic signs, nonemergency egress signs, variable message boards, lane signals, and lane signal fixtures. These systems range from simple signs to complex variable message boards. The requirements for roadway signs are established in the Manual on Uniform Traffic Control Devices.

http://mutcd.fhwa.dot.gov/pdfs/2009r1r2/mutcd2009r1r2edition.pdf

Traffic signs – Traffic signs consist of the traffic sign and supports. Signs for pedestrian egress, variable message signs, and lane signals are not covered under this element.
Egress signs – These elements consist of egress signs and their supports that are not directly related to the emergency lighting system. Proper illumination is necessary to read these signs under emergency conditions.

Variable message boards – Variable message boards consist of the variable message board, supports, associated electrical connections, and computer hardware. These sophisticated devices contain display modules, drivers, power supplies, sensors, fans, dust filters, control cabinets, controllers, input/output circuit boards, modems, and computerized systems.

Lane signals – Lane signals include the lane signal devices, their supports and the control system and some or all of the following subcomponents: signals/fixtures, control station, control cabinets, and conduit.
Lane signal fixtures – Lane signal fixtures include the fixtures, the supports, and the wiring.

5.3.3.7 **Protective systems**

Protective systems include the protective coating for steel corrosion, concrete weathering, and fire protection.

Steel corrosion protective coating – Steel corrosion protective coating systems include paint, galvanization, or other top coat steel corrosion inhibitor. Additional information on corrosion protection can be found at:

http://www.fhwa.dot.gov/bridge/steel/pubs/if12052/volume19.pdf

Concrete corrosion protective coating – Concrete corrosion protective coating systems include silane/siloxane water proofers, crack sealers such as High Molecular Weight Methacrylate (HMWM), or any top coat barrier that protects concrete from deterioration and reinforcing steel from corrosion.

Fire protective coating – Fire protective coatings include the coating applied to tunnel elements to protect these components from fire.

5.4 Load Rating

Load rating is the determination of the safe vehicular live load carrying capacity. Load ratings are performed using structural plans and information gathered from inspections. The results of the load rating may include load posting to ensure that the roadway has a load capacity equal to or greater than the legal loads or unrestricted routine permit loads for the particular State. A load rating evaluation may be required for issuing hauling permits. A load rating is required for all tunnels that:

- Have a structurally supported roadway system to carry vehicles (not at grade) within the tunnel bore (Figure 5.8 A). The roadway system that carries the vehicles can be treated like a bridge, with a deck, stringers, floor beams, and other members, as applicable.
- Are subjected to live load force effects from a roadway located above the tunnel (Figure 5.8 B). The tunnel liner can be treated like a culvert where earth pressures and live (truck) loads are distributed through fill.

Figure 5.8 – Load rating of tunnels. A) Structurally supported floor; B) Overhead roadway.

The load rating of tunnels shall follow the provisions from the AASHTO Manual for Bridge Evaluation (MBE). In cases where the AASHTO criteria are silent or do not apply, criteria should be agreed upon between the tunnel owner and engineer performing the evaluation, and a record of these decisions shall be documented in the tunnel file. Tunnel ratings are based on information in the tunnel file, including the results from recent field inspections. It is recommended that a qualified geotechnical engineer assist with the evaluation of soil-structure interaction between the tunnel liner, any adjacent elements, and the ground (Figure 5.9).

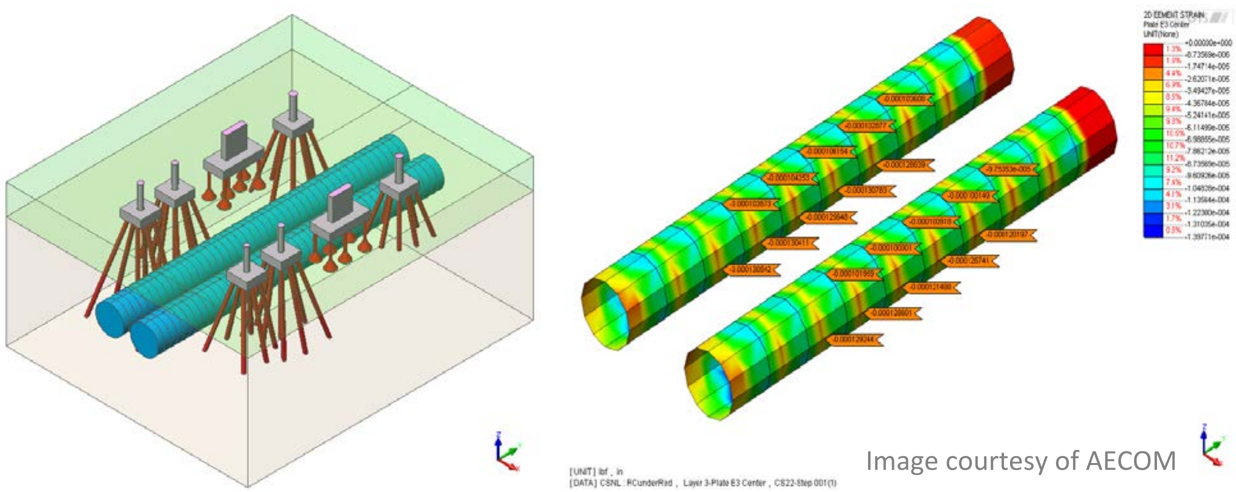

Figure 5.9 – Finite element analysis to mode soil structure interaction.

The load rating may be a simple load rating based on design information, or it may require further engineering analysis. As part of every inspection cycle, tunnel load ratings should be reviewed and updated to reflect any relevant changes in condition or loading noted during the inspection. In the event of a structural or loading condition change at any stage of its service life that may reduce the live load carrying capacity, load ratings should be re-evaluated and updated. Load rating may require a field visit to verify the structural condition.

5.4.1 **Selection of Load Rating Method**

Section 6 of the AASHTO MBE specifies the load rating and posting criteria for highway bridges. Section 8 of the MBE includes the method and criteria for Nondestructive Load Testing for bridge load rating. Load rating and posting for tunnels subject to highway vehicular loads should use the criteria detailed in Sections 6 or 8 of the MBE.

Section 6A of the MBE introduces the Load and Resistance Factor Rating (LRFR) Method, and Section 6B discusses the Allowable Stress Rating (ASR) Method and the Load Factor Rating (LFR) Method. The Federal Highway Administration has issued several policy memoranda regarding the selection of load rating methods. The appropriate load rating method for load rating and posting of tunnels should be selected following FHWA's policy memoranda. Links to these memoranda follow:

Bridge Load Ratings for the National Bridge Inventory, December 22, 1993:

(http://www.fhwa.dot.gov/legsregs/directives/policy/dec22.htm)

This policy memorandum requires that all NHS bridges be rated by the LFR method after 1995.

Bridge Load Ratings for the National Bridge Inventory, October 30, 2006:

(http://www.fhwa.dot.gov/bridge/nbis/103006.cfm)

This policy memorandum further clarifies the selection of load rating methods based on the design method and types of bridges.

The following section will briefly introduce the AASHTO LRFR method only. Refer to Sections 6 and 8 of the MBE for detailed criteria of the LRFR and other load rating methods.

5.4.2 **Load and Resistance Factor Rating (LRFR)**

Tunnel load ratings are performed for various purposes using different live load models and evaluation criteria. Models are used to evaluate the design live load, legal loads, and permit loads. This section describes a systematic approach to tunnel load rating for these load models using the load and resistance factor philosophy; and it aims to address the different uses of load rating results, consistent with the MBE.

The methodology for the load and resistance factor rating of tunnel members is comprised of three distinct procedures:

1) Design load rating
2) Legal load rating
3) Permit load rating

The results of each procedure serve specific purposes and also guide the need for further evaluations to verify tunnel safety or service level. A detailed rating flow chart is included in Appendix A6A in the MBE.

5.4.2.1 **Design Load Rating**

Design load rating is a first-level assessment of tunnel members based on the HL-93 loading and Load and Resistance Factor Design (LRFD) standards, using dimensions and properties of the tunnel in its present as-inspected condition. It is a measure of the performance of existing tunnel members to current LRFD bridge design standards. Under this check, tunnel members are screened for the strength-limit states at the LRFD design level of reliability. Evaluation at a second lower evaluation level of reliability is also an option.

Design load rating can serve as a screening process to identify tunnels that should be load rated for legal loads. Tunnel members that pass the design load check ($RF \geq 1$) at the Inventory level will have satisfactory load rating for all legal loads (and routine permit loads in various States) that fall within the LRFD exclusion limits.

5.4.2.2 **Legal Load Rating**

This second level rating provides a single safe load capacity (for a given truck configuration) applicable to AASHTO and State legal loads. Live load factors are selected based on the truck traffic conditions at the site. Strength is the primary-limit state for load rating; service-limit states are selectively applied. The results of the load rating for legal loads could be used as a basis for load posting or tunnel member strengthening.

5.4.2.3 **Permit Load Rating**

Permit load rating checks the safety and serviceability of tunnel members in the review of permit applications for the passage of vehicles above the legally established weight limitations. This is a third-level rating that should be applied only to tunnels having sufficient capacity for AASHTO legal loads. Calibrated load factors by permit type and traffic conditions at the site are specified for checking the load effects induced by the passage of the overweight truck. Guidance is also provided on the serviceability criteria that should be checked when reviewing permit applications.

5.4.2.4 **Load Rating Equation**

The following general expression should be used in determining the load rating of each component and connection subjected to a single force effect (i.e., axial force, flexure, or shear):

$$RF = \frac{C \pm \gamma_{DC}DC \pm \gamma_{DW}DW \pm \gamma_{EV}EV \pm \gamma_{EH}EH \pm \gamma_{ES}ES \pm \gamma_{P}P}{(\gamma_{LL})(LL+1M) \pm \gamma_{LS}LS}$$

In which, for the Strength Limit States:

$$C = \varphi_c \, \varphi_s \, \varphi \, R_n$$

Where the following lower limit shall apply:

$$\varphi_c \, \varphi_s \geq 0.85$$

And, for the Service Limit States:

$$C = f_R$$

where:

RF = Rating factor

C = Capacity

f_R = Allowable stress specified in the LRFD code

R_n = Nominal member resistance (as inspected)

DC = Dead load effect due to structural components and attachments

DW = Dead load effect due to wearing surface and utilities

EV = Vertical earth pressure

EH = Horizontal earth pressure

ES = Uniform earth surcharge

LS = Live load surcharge

P = Permanent loads other than dead loads

LL = Live load effect

IM = Dynamic load allowance

γ_{DC} = LRFD load factor for structural components and attachments

γ_{DW} = LRFD load factor for wearing surfaces and utilities

γ_{EV} = LRFD load factor for vertical earth pressure

γ_{EH} = LRFD load factor for horizontal earth pressure

γ_{ES} = LRFD load factor for uniform earth surcharge

γ_{LS} = LRFD load factor for live load surcharge

γ_{P} = LRFD load factor for permanent loads other than dead loads = 1.0

γ_{LL} = Evaluation live load factor

φ_c = Condition factor

φ_s = System factor

φ = LRFD resistance factor

5.4.2.5 **Limit States**

The load rating should be carried out at each applicable limit state and load effect, with the lowest value determining the controlling rating factor. Limit states and load factors for load rating should be selected from the MBE.

Components subjected to combined load effects should be load rated considering the interaction of load effects (i.e., axial-bending interaction or shear-bending interaction).

5.4.2.6 **Resistance Factors**

Use of Condition Factors as presented below may be considered optional based on an agency’s load-rating practice.

The condition factor provides a reduction to account for the increased uncertainty in the resistance of deteriorated members and the likely increased future deterioration of these members during the period between inspection cycles.

System factors are multipliers applied to the nominal resistance to reflect the level of redundancy of the complete superstructure system. Tunnel components that are less redundant will have their factored member capacities reduced and, accordingly, will have lower ratings.

The system factors in Table 6A.4.2.4-1 of the MBE are more conservative than the LRFD design values and may be used at the evaluator’s discretion until they are modified in the AASHTO LRFD Bridge Design Specifications.

5.4.3 **Loads and Load Distribution**

Simplified live load distribution equations specified in AASHTO LRFD Design Specifications Article 4.6.2 should be used in load rating analysis as appropriate.

5.4.4 **Refined Structural Analysis**

Tunnel members may be analyzed by refined methods of analysis as described in AASHTO LRFD Design Specifications Article 4.6.3 when they exhibit insufficient load capacity when analyzed by approximate methods. Tunnels or loading conditions for which accurate live load distribution formulas are not readily available can also use these methods.

5.4.5 **Load Rating Based on Engineering Judgment**

In instances where necessary details, such as reinforcement in the tunnel, are not available from plans or field measurements, a physical inspection by a qualified inspector and evaluation by a qualified engineer may be sufficient to establish an approximate load rating based on rational criteria.

Stringer-supported concrete deck slabs and metal decks that are carrying normal traffic satisfactorily need not be routinely evaluated for load capacity. The decks should be inspected regularly to verify satisfactory performance. The inspection of metal decks should emphasize identifying the onset of fatigue cracks.

5.4.6 **Documentation of Load Rating**

The load rating should be fully documented including all background information such as field inspection reports, material, and load test data, all supporting computations and a clear statement of all assumptions used in calculating the load rating. If a computer model was used, the input data file should be retained for future use.

5.4.7 **Quality Assurance and Quality Control**

Quality control procedures are intended to maintain the quality of the bridge load ratings and are usually performed continuously within the load rating teams or unit. When a consultant performs load ratings, the consultant must have quality control procedures in place to ensure the accuracy and completeness of the load ratings. All load rating calculations must be checked by a qualified engineer other than the load rating engineer. Upon completion, the initials of the reviewer are to be placed on every sheet of the calculations.

Quality assurance procedures are used to verify the adequacy of the quality control procedures to meet or exceed the standards established by the agency or the consultant performing the load ratings. Quality assurance procedures are usually performed independently of the load rating teams on a sample of their work. Guidance on quality measures for load rating may be found in MBE Article 1.4.

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Appendix A – Tunnel Vulnerability Assessment

Risk-Based Prioritization of Terrorist Threat Mitigation Measures on Highway Tunnels

Bruce A. Walton, P.E. Texas, Tim Campbell, P.E. Nebraska, Greg Jizba, P.E. Nebraska, and Matt Tomanek, P.E. Nebraska[1]

Abstract: This paper describes a risk-based methodology developed to facilitate prioritization of terrorist threat mitigation strategies on individual tunnels. Numerous risk-based methods have been used for prioritization among a group of tunnels or other assets. However, this methodology is unique in that it is specifically designed to focus on a single tunnel. Two separate risk analyses are implemented for each tunnel. One is a component-based risk analysis to evaluate the risk to operational closure of the tunnel. Vulnerability for operational closure is defined as the threat size that causes catastrophic damage leading to Operational Loss of Service (OLS) of at least three months. The second is a scenario base risk analysis to evaluate the risk of casualties in the tunnel. Vulnerability for the casualty risk analysis is defined as a function of the number of casualties for the scenario. “Risk,” as discussed herein, describes the relative potential for a terrorist attack and the associated consequence from the attack. It is based on such factors as the threat likelihood, the component or scenario location and thus accessibility to terrorists, and component resistance to the specific threat. The component-specific risk factors and their modifying attributes are described. The result of the methodology is a relative risk-ordered list of components or scenarios for terrorist attacks, allowing prioritization and optimization of the mitigation design for the tunnel. Once mitigation schemes are identified, the methodology can then be used to recalculate mitigated risk and the relative risk reduction and mitigation costs to provide a cost to benefit value. The methodology and comparison criteria are described, and a simple application example is given to demonstrate the use of the methodology.

CE Database subject headings: Tunnels; Remedial action; Risk management; Terrorism; Tunnel safety and security.

Introduction

The tragic events of September 11, 2001 and direct threats to several major bridges and tunnels soon after brought the realization to the federal government and infrastructure owners and operators that action regarding transportation security was needed. Limited resources and competing needs for infrastructure investment have led owners to consider a combination of preparedness, response, mitigation, and risk acceptance to address security threats.

Although many owners have developed their own highway asset prioritization methodology, the most widely used have been those developed under funding from the National Cooperative Highway Research Program (AASHTO 2002 and NCHRP 2009). Some of the common prioritization criteria have included: function within the infrastructure system (i.e., major traffic, emergency, or defense route), economic importance, symbolic importance, public impact if attacked, cost and time to replace, and relative likelihood of and vulnerability to an attack. Most of the methodologies are risk based and applied statewide or on a system of infrastructure. The

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goal of these risk processes is to develop a rational basis for security investments, understanding that a zero-risk answer is not usually possible or affordable and that terrorist threats are ever-evolving and adaptive. While risk cannot be totally eliminated, there are practical strategies available to reduce risk within available budgets.

Since September 11, 2001, most asset owners have completed their prioritizations and have begun or are ready to begin mitigation efforts on their highest priority structural assets. Thus, prioritization is again required, this time at the individual structure level. Instead of prioritizing among a group of structures, the owner must now prioritize among the individual components on a given structure to determine which are the most in need of terrorist threat mitigation efforts. While the problem is very similar, the asset prioritization methods that compare assets based on socioeconomic factors affecting the entire infrastructure system are not directly applicable to this more focused problem.

This paper describes a dual risk assessment methodology as developed by the writers. The methodology is based on the risk-based methodology developed by James Ray (2007) for bridge structures, and uses similar factors and threats. Two separate risk analyses are implemented for a tunnel. One is a component-based risk analysis to evaluate the risk to operational closure of the tunnel. Vulnerability for operational closure is defined as the threat size that causes catastrophic damage leading to OLS of three months. The second is a scenario-based analysis to evaluate the risk of casualties in the tunnel. Vulnerability for the casualty risk analysis is defined as a function of the number of casualties for the scenario. The process is based on the risk equations commonly used for natural hazard risk assessments.

This methodology was developed to assess tunnel risk for the Transportation Security Administration's Highway Motor Carrier Branch, and it has recently been utilized on several major tunnels in the United States. It has provided consistent and reliable analysis among different tunnels and proven effective for prioritizing the use of limited mitigation funds. The methodology is presented here as it was used. However, it should be emphasized that any new procedure can evolve and improve as experience is gained with it. Risk-based methods particularly benefit from the accumulation of data that can better support probabilistic risk factors. One purpose of this paper is to present the methodology as it was used and stimulate input and suggestions from others for its continued improvement.

Threats

There are unlimited possibilities as to the types of terrorist threats that could be brought against tunnel structures (AASHTO 2003). For purposes of the work herein, the authors have grouped threats into the following basic categories:

Vehicleborne improvised explosive devices (VBIED): These include land borne vehicles (i.e., truck bombs) deployed against components reachable by land and waterborne vehicles (i.e., boat bombs) deployed against components reachable by water.

Hand-emplaced IED (HEIED): These include contact explosive devices such as satchel demolition charges and shaped charges that are commonly used by military engineers and civilian demolition experts to precisely cut or sever structural members. For water-based HEIED attack, this includes IED's placed or dropped in water. There are a myriad of varieties and sizes of HEIEDs and as with VBIEDs, the likelihood of their use should decrease as charge sizes increase.

Nonexplosive cutting device (NECD): These include non- explosive devices such as saws, grinders, and torches that can be used to cut or sever structural members. There are multiple options for this purpose, and some are very effective for cutting large structural members.

Vehicular impact (VI): Like VBIEDs, these include land-borne and waterborne vehicles. The VI threat includes water-borne vessel impact, sunken ship impact, anchor drop, or anchor drag.

Fire: Fire of sufficient size and duration can cause structural damage such as spalling and loss of member strength and stiffness. Thus, a "pool fire" from a ruptured tanker truck, cargo fire, or vehicle fire adjacent to key components is of great concern.

Industrial Chemical Vehicle Spill (ICS): An ICS in a tunnel can cause tunnel closure and casualties. An ICS from a pressurized tank for a lighter than air and heavier than air chemical is used in the casualty risk calculations.

Basic Risk Equation

Risk can be determined many ways, and one general form is:

$$\text{Risk} = f(I,O,V) \qquad (1)$$

where:
I = importance
O = occurrence
V = vulnerability

This is a general risk equation used for many purposes such as natural hazard vulnerability assessments (AASHTO 2003), and it is used herein for security mitigation prioritization of individual tunnel components and scenarios. The value for risk is the product of the three factors: I, O, and V. Each factor is assigned attribute values, and each attribute is given a weighting factor. The attributes and weightings combine to produce values for I, O, and V, representing a quantitative measure for each aspect of total risk.

The following is a discussion of the two separate risk analyses that use the formula above to evaluate tunnel risk. First the Operational Loss of Service risk procedure is discussed; and then the Casualty risk procedure is discussed.

Operational Risk Assessment Methodology

The component risk analysis used in this report determines the relative risk caused by the threats to components of a tunnel. The risk assessment methodology includes the following main elements:

General Risk Equation

For the operational loss of service risk assessment factors I, O, and V, are defined and assigned attributes as follows:

Importance refers to the significance of the component to the tunnel and has two attributes:

- Operational importance
- Repair cost

Occurrence refers to the likelihood of a threat being used against a component and has four attributes:

- General likelihood of threat taking place
- Likelihood of threat being used against component
- Target attractiveness
- Access to component

Vulnerability refers to the severity of threat that causes a tunnel closure of 3 months of more.

Component Risk Analysis

Tunnel components have differing operational importance, vulnerability, and access for attack. An effective methodology can enumerate these attributes to compare component criticality and mitigation effectiveness, producing a quantified measure of varied mitigation schemes for an individual tunnel. Building on the basic equation discussed earlier, a more detailed formula to produce these measures is described in the following equation:

$$\mathbf{R}_{ij} = \mathbf{I}_j \, \mathbf{O}_{ij} \, \mathbf{V}_{ij} \qquad (2)$$

where:
j = individual tunnel component
i = basic threat

I_j = Importance of an individual component, j, to the tunnel, considering both its contribution to overall operations and repair cost.

O_{ij} = A measure of the relative probability of a basic threat, i, actually occurring against the given component, j, considering such factors as general likelihood of the threat, visibility or attractiveness of the component, and access to the component.

V_{ij} = A measure of the relative vulnerability of the given component, j, given the occurrence of the basic threat, i, and considering the components resistance to the threat.

Each of the above-described factors is a number between 0 and 1. The factors are computed using a summation of the weighted attributes that define the factors as follows:

$$\mathbf{I}_j = \Sigma\, [\mathbf{wf}_k \bullet \mathbf{a}_{kj}]_j \qquad (3)$$

$$\mathbf{O}_{ij} = \Sigma\, [\mathbf{wf}_k \bullet \mathbf{a}_{kij}]_{ij} \qquad (4)$$

$$\mathbf{V}_{ij} = \Sigma\, [\mathbf{wf}_k \bullet \mathbf{a}_{kij}]_{ij} \qquad (5)$$

where:
wf_k is the weighting factor applied to the attribute, a_{kij}.
and $\mathbf{\Sigma}\ wf_k = 1.0$

Attributes are specific unity-based criteria of varied importance that are weighted, then summed together to define each risk factor.

The O and V factors (i.e. O_{ij}, V_{ij}) are the result of component, *j*, vulnerabilities to the following threats, *i*:

- Vehicle-Borne Improvised Explosive Device (VBIED)
- Hand-emplaced IED: (HEIED)
- Non-explosive cutting device (NECD)
- Vehicular Impact ; including land or water based vehicles (VI)
- Fire
- Industrial Chemical Spill (ICS)

Importance Factor, I_j

Eq. (3) is used to calculate the importance factor. It measures the importance of an individual component, j, to the tunnel operations, considering the following attributes.

Operational Importance of the Component

This attribute captures the importance of the component to the overall operational capability of the tunnel. This is the most important attribute for this factor in that the worst possible outcome of an attack would be total closure of the tunnel.

The following values are used for the operational importance attribute, depending upon the component type:

1. Importance of the individual main tube component to overall tunnel operation. Redundancy can be structural redundancy or operational redundancy.
    - 1.00 = Very critical, even a small failure is critical, with no redundancy. Examples are a submerged tube or some components of a single bore tunnel such as the liner or portal.
    - 0.75 = Important component, but may have alternate path(s) such as components of dual tubes and compression members in supported structures.
    - 0.50 = Important component, but has alternate path(s) such as bracing in supported structures.
    - 0.25 = Important component, but has a definite redundancy or alternate path.
    - 0.00 = Not critical to overall operation, such as floor systems or waterproof liners in hard rock.

2. Importance of a Utility Component such as pump, ventilation equipment and ductwork, lighting, and emergency communication systems.
    - 1.00 = Critical with no redundancy (Ventilation ducts in semi-transverse ventilation system, primary power controls in ventilation buildings, and a system of jet fans).
    - 0.75 = Critical, dispersed or with redundancy (power supply to ventilation building when fed from more than one power grid; vent fans when multiple fans are present; and exhaust or fresh air duct in full transverse ventilation system with multiple zones).

- 0.50 = Important with no redundancy.
- 0.25 = Important, dispersed or with redundancy (individual jet fans when many jet fans are dispersed along tunnel).
- 0.00 = Non critical (Components used for maintenance or normal drainage).

Ventilation may be important for tunnels less than 1000 ft. long; but it is usually critical for operation of tunnels over 1000 ft long.

Relative Repair Costs for the Component if Damaged

This attribute is important for cases where the component damage may cause similar tunnel closure times, but the repair cost may be much higher for one or the other. The following values are recommended:

- 1.00 = Very high (submerged tube, shield in soft soil).
- 0.75 = High (Ventilation Building in tunnel over 1000 ft. long; portal in unstable soil or under a steep slope; operation center).
- 0.50 = Medium (Ventilation building in tunnel under 1000 ft. long; overhead vent ductwork in transverse ventilation systems; electrical power and lighting systems; firefighting systems and equipment).
- 0.25 = Low (tube in hard rock; column; wall; slab; portal in rock; shallow cut and cover liner or portal; roadway on soil).
- 0.0 = Little to no cost.

Occurrence Factor, O_{ij}

This factor is calculated with Eq. (4) and measures the relative likelihood of a basic threat, *i*, actually occurring against the given component, *j*, as described below:

The importance and vulnerability factors can be rigorously and objectively defined through various calculations. However, the occurrence factor is quite subjective and does not represent an actual probability. Instead, it is a measure of the subjective expectation that threat *i* will occur compared to the other threats.

General Threat Likelihood

This attribute describes the general likelihood that attackers prefer this type of threat compared to others. For example, history has shown that many terrorists prefer VBIEDs over HEIEDs. Even more, very few in the past have chosen non-explosive options, and even fewer have chosen fire or impact.

This attribute will be the same, regardless of the component under consideration. Therefore, the likelihood of a VBIED should be considered independently of which component is being examined. The likelihood that the given threat will be used against a given component is covered separately. Values used for general threat likelihood are:

- 1.00 = very likely
- 0.75 = likely
- 0.50 = somewhat likely
- 0.25 = slightly likely

- 0.00 = not likely

Likelihood of Given Threat Against Given Component

This attribute addresses the likelihood of the given threat being used against an individual component under consideration. For example, non-explosive cutting devices are not very effective against reinforced concrete elements. So there is a low likelihood that a terrorist will choose this type of weapon to attack a component such as a reinforced concrete liner or portal. It is much less likely that a terrorist will use a shaped charge against a hard rock tunnel liner than a vehicle bomb.

Component access issues are not considered here. These issues are addressed separately by the "access" attribute. Also, threat size is not considered here as that is addressed separately with the *vulnerability factor*. Values used herein for this attribute are:

- 1.00 = very likely
- 0.75 = likely
- 0.50 = somewhat likely
- 0.25 = slightly likely
- 0.00 = not likely

Visibility or Attractiveness of the Component

Independent of threat type, this attribute reflects the likelihood that an attacker will recognize that the component is critical to tunnel operations. It attempts to capture the fact that the importance of some components is not always obvious to lesser-informed persons. For example, everyone knows that a waterproof membrane is critical to the portion of a hard rock tunnel that passes through an underground water source, and that the structural liner in an area with poor soil is more critical than the structural liner in a hard rock area, but it is much less likely that they will know exactly where the critical areas are located. It is recognized that it is dangerous to underestimate attackers and their capabilities to understand their targets. As a result, this variable is given a low weighting factor. Values for this attribute are:

- 1.00 = high; (submerged tubes; poor soil area that are well defined; columns in air rights structures; vent tower/structures)
- 0.75 = medium (tunnel liners in normal soil)
- 0.50 = low; (parallel emergency tunnels; vent tower or structures not attached directly to main tunnel)
- 0.25 = very low (utilities away from main tunnel or in separate structures)
- 0.00 = not attractive

Access to the Component

This attribute addresses the ease of access to an individual component for delivery of the threat under consideration before a capable response occurs.

Ease of access leads to added time on the target for an aggressor, i.e., more time to carry out the attack. Thus, this attribute is a function of access time (AT) versus response time (RT). Note that AT only includes the time required to reach the component with the threat and does not include the time to actually carry out the threat, i.e., inflict the damage. Time to carry out the threat after reaching the component is covered under the vulnerability factor as appropriate. Values used for this attribute are:

- 1.00 = completely accessible, RT™AT
- 0.75 = RT probably > AT
- 0.50 = RT=AT
- 0.25 = RT probably < AT
- 0.00 = access is completely denied, or you are confident that AT™RT

Vehicle Restrictions greatly reduce the Likelihood for larger vehicle attacks that use VBIEDs, fire, and chemical attacks in tunnel. Consider types of vehicles allowed in tunnel, such as heavy goods vehicles (HGV) and dangerous goods vehicles (DGV). Values used for this attribute are:

- 1.00 = Very likely, HGV and DGV allowed with normal traffic
- 0.90 = Likely, HGV allowed with normal traffic, no DGV
- 0.80 = Somewhat likely, size restrictions, no HGV or DGV
- 0.70 = Slightly likely
- 0.00 = access is completely denied

While the standoff distance of a VBIED to the component might be considered an access issue, it is not accounted for here. It is accounted for under the vulnerability factor where an increased standoff will make the component less vulnerable to the given threat. For this attribute, a value of 1.0 is used for a VBIED occurrence because it can always get somewhere in the vicinity of the component and it is just a matter of how close it can get, i.e., standoff and the resulting effectiveness of the VBIED.

The same logic is used for access consideration of impact threats. The presence of traffic barriers, pier dolphins, fenders, rock covers, etc., that actually limit access is accounted for under the vulnerability factor where the components are shown to be more resistant to impact if protected by a barrier.

For the fire threat, this attribute is considered purely in terms of access time and not the time required in reducing component strength once heating begins. This time is captured under the *fire vulnerability* factor. This attribute considers if the response will occur before the fire reaches the component and starts heating it. Fire control systems can be accounted for here because the response can occur more quickly and thus the heat will not reach the component as quickly, if at all.

Vulnerability Factor, V_{ij}

Eq. (5) is used to calculate the vulnerability factor. It captures the relative vulnerability of the given component, *j*, given the occurrence of the basic threat, *i*. In this case, the only attribute modifying the vulnerability factor is the resistance of the component to the given threat. These can, however, be very difficult questions to answer, often requiring detailed blast analyses or reference to military demolition manuals.

Note that "catastrophic damage" implies that the component would be damaged to such an extent that it causes specified down time or closure of the tunnel, where the tunnel is closed for more than 90 days.

Suggested vulnerability factor (V) values are described in the following sections.

Resistance to VBIED

Resistance to this threat is defined by the amount of explosives (i.e., the size of VBIED) required to cause "catastrophic damage" to a component when the bomb is at a specific location relative to the component. Explosive weight values are used for both land and water borne vehicles. The values are given by:

- 1.00 = catastrophic damage with less than *x* lbs explosive weight
- 0.90 = catastrophic damage with *x* to 6*x* lbs explosive weight
- 0.50 = catastrophic damage with 6*x* to 10*x* lbs explosive weight
- 0.30 = catastrophic damage with 10*x* to 20*x* lbs explosive weight
- 0.10 = catastrophic damage with 20*x* to 60*x* lbs explosive weight
- 0.05 = catastrophic damage with 60*x* to 120*x* lbs explosive weight
- 0.00 = not applicable or can withstand all of the above-mentioned threats.

For a specific analysis, a value of *x* would be chosen to capture the potential vehicle bomb sizes. Higher values (closer to 1.0) for smaller VBIED's reflect the easier logistics for an aggressor to accumulate small explosive quantities and deliver them to the tunnel undetected. Unlike the attribute values for the previously discussed factors, the VBIED values do not have a linear relationship with explosive weight, largely because of the increasing difficulty obtaining and using larger quantities.

These weights were derived using the analytical hierarchy methodology (Ragsdale 2002), and the bomb sizes used in the process were based on the developer's knowledge of past event bomb sizes. These factors show that, based on historical events, larger VBIEDs are much less likely than smaller ones. The above-presented values are actually considerably more conservative than historical events would strictly indicate. This was done as a basis for a general comparison because it is recognized that it is difficult to reliably predict future terrorist behavior based on past events.

For redundant components, only consider here the bomb size required to take out one of the components. For the procedure herein, redundancy and its effect on risk is captured under the importance factor previously described.

Resistance to HEIED

Resistance to this threat is defined in terms of the amount of explosives (i.e., the size of HEIED) required to cause catastrophic damage (defined earlier) when the threat is properly placed on the component. There are many HEIED types, so for each component, consider the HEIED to which the given component will be most vulnerable. The specific HEIED considered for each component will vary as some components are more vulnerable to one type of HEIED than another. The vulnerability values for HEIED's are:

- 1.00 = catastrophic damage with less than *y* lbs explosive weight
- 0.95 = catastrophic damage with >*y* to 2*y* lbs explosive weight
- 0.70 = catastrophic damage with >2*y* to 10*y* lbs explosive weight
- 0.20 = catastrophic damage with >10*y* to 20*y* lbs explosive weight
- 0.10 = catastrophic damage with >20*y* to 100*y* lbs explosive weight

- 0.05 = catastrophic damage with greater than 100*y* lbs explosive weight
- 0.00 = not applicable or can withstand all of the abovementioned threats

For a specific analysis, a value of *y* would be chosen to capture the potential hand carried explosive sizes expected. Higher explosive weight requirements here indicate less risk because it is logistically more difficult to obtain and deliver large explosive quantities. As discussed previously for the VBIEDs, the above-mentioned weights do not have a linear spread. These values were also derived using the analytical hierarchy process (Ragsdale 2002) and reflect bomb size likelihood based on past HEIED events.

For a water-based HEIED attack, include an IED placed or dropped in water.

As with VBIEDs, the HEIED size required to take out one of the components is only considered, even if there are redundant components. For the procedure herein, redundancy and its effect on risk is captured under the importance factor as previously described.

Resistance to NECD

Resistance to this threat is defined by the time to cut or sever the component. Here "cut" implies that the component would be cut sufficiently so that it could not carry out its required function. Partial damage is not considered. The vulnerability values for NECD are:

- 1.00 = time to cut "very short" per component, less than *z* min.
- 0.50 = time to cut from z to 2*z* min per component.
- 0.10 = time to cut from 2*z* to 6*z* min per component.
- 0.05 = time to cut greater than 6*z* min.
- 0.00 = not applicable or not vulnerable to cutting

For a specific analysis, a value of *z* would be chosen to capture the potential time range expected. The values shown reflect the fact that components that take less time to cut are at higher risk. While not rigorously developed from past events (none exist for a basis), the weights shown reflect the likelihood that an attacker would choose the NECD based on the degree of difficulty in cutting.

Resistance to Impact

Resistance to this threat is defined by the size and weight of vehicle required for catastrophic damage (defined previously) of the given component. This applies to land-based and water based components accessible by vehicles and to water-borne impact from vessels or anchor drag. All vehicles are assumed to be at maximum attainable speed for the approach to the given component. The presence of impact barriers should be considered here because they protect a component, making it more resistant to impact.

The impact vulnerability values for land-based vehicles are:

- 1.00 = catastrophic damage from a car or SUV impact
- 0.75 = catastrophic damage from a panel van (H-20) impact
- 0.50 = catastrophic damage from a semi-truck (HS-20) impact
- 0.00 = not applicable or can withstand all of the abovementioned threats

The vulnerability values for water vessels are:

- 1.00 = catastrophic damage from a small vessel impact
- 0.75 = catastrophic damage from a typical vessel impact
- 0.10 = catastrophic damage from a large vessel impact
- 0.00 = not applicable or can withstand all of the abovementioned threats

Values for small, typical and maximum size ships will vary depending on the waterway. Use descriptions of small, typical, and maximum size vessels available from the US Coast Guard, or use site-specific data provided by tunnel owner.

Resistance to Fire

Resistance to fire is defined as the size of device that causes catastrophic damage requiring tunnel closure for 90 days. Do not consider the time for fire to reach the component as that is captured under “threat access.” Threat size is defined by the Energy Output of the fire in megawatts (MW). The values listed below reflect the "probability" of that threat size occurring. Note that there have been many relatively small tunnel fires, but few have been above 100 MW. The vulnerability values for fire are:

- 1.00 = Catastrophic damage with < = v MW fire)
- 0.98 = catastrophic damage with v to $3v$ MW fire
- 0.95 = catastrophic damage with $3v$ to $6v$ MW fire
- 0.85 = catastrophic damage with $6v$ to $20v$ MW fire
- 0.50 = catastrophic damage with $20v$ MW to $60v$ MW fire
- 0.00 = not applicable or not vulnerable to fire.

For a specific analysis, a value of v would be chosen to capture the range of fire sizes expected. The resistance to fire variable can change with the addition of hardening, increased standoff, fire protection, fire fighting capability, and operating procedures.

The factors reflect the likelihood that an attacker would choose fire as an attack method. Attackers should be less likely to choose fire against a component that is very fire resistant, thus it is at much less risk than one that would quickly lose its strength.

Resistance to Chemical Release

Resistance to an ICS is defined as the size of device that causes catastrophic damage, clean-up, or decontamination requiring tunnel closure for 90 days. Do not consider the time for fire to reach the component as that is captured under “threat access.” Threat size is defined by the volume of chemicals spilled. The values listed below for ICS vulnerability reflect the "probability" of that threat size occurring.

- 1.00 = catastrophic damage with < = w-gal tank
- 0.98 = catastrophic damage with >w to $5w$-gal tank
- 0.95 = catastrophic damage with >$5w$- to $10w$ gal
- 0.85 = catastrophic damage with >$10w$- to $25w$ gal van, Local transport
- 0.70 = catastrophic damage with >$25w$- to $50w$ gal van
- 0.60 = catastrophic damage with >$50w$- to $70w$ gal truck, long distance transport
- 0.50 = catastrophic damage with >$70w$- to $90w$ gal truck, long distance transport

- 0.00 = not applicable or not vulnerable

For a specific analysis, a value of *w* would be chosen to capture the range of chemical releases expected. The factors reflect the difficulty for an attacker in obtaining and bringing larger threats to the tunnel and successfully executing an attack. Industrial Chemical Threats are seen as the most likely and easiest Chemical-Biological-Radiological (CBR) threat for an aggressor to carry off successfully against a highway tunnel.

Weighting Factors for Attributes, wf_k

The attributes affecting the three risk factors (i.e., I, O, V) have been described in detail earlier. Expert elicitation has shown that some of the attributes should have a larger effect (weight) on the risk factors than others.

For example, the "operational importance" attribute should have much more weight on the importance factor than the "general threat likelihood" attribute. That attribute is important to differentiate two components when all other modifying attributes are equal, but it certainly should not carry as much weight as the operational aspect. The "wf_k" weight factors in Eqs. 3 thru 5 are used for this purpose.

These factors were derived using the pair wise comparison procedure of the analytical hierarchy process. This method provides a systematic and consistent way to develop weight factors among a group of related variables. As there are no detailed data on the relationship between most of these variables, the input to the comparison matrices is subjective but informed by input from many knowledgeable sources. During development of these factors, several expert sources were asked to assign a numeric value to the relative importance of one attribute over another. The resulting weighting factors used are shown in Table 1 below.

Table 1 Component Risk Weighting Factors

Occurrence		**Vulnerability**		**Importance**	
General Threat Likelihood	0.10	Resistance to Threat	1.00	Operational Importance	0.65
Threat Likelihood Against Component	0.35			Repair Cost if Damaged	0.35
Visibility or Attractiveness of Component	0.10				
Threat Access to Component	0.45				
Sum	1.00	Sum	1.00	Sum	1.00

Casualty Risk Assessment Methodology

A scenario-based risk assessment procedure is used to evaluate the risk of casualties in a highway tunnel from a terrorist attack. The casualty risk analysis procedure starts by selecting a threat scenario consisting of a threat size and location and then evaluating the current and mitigated casualties caused by that threat scenario. The risk reduction value is based on the change in the number of casualties for the un-mitigated and mitigated cases. NCHRP proposed a scenario approach in "Making Transportation Tunnels Safe and Secure." The casualty risk analysis used here builds on this concept to quantify the relative casualty risk caused by multiple scenarios. The process uses the basic risk equation described earlier, but unique to this methodology are the detailed casualty calculations.

Basic Risk Equation

Risk (R) is evaluated as a function of multiple factors to produce a quantitative measure of risk. The basic risk equation, Eq. (1), is the same as for the operational out of services risk calculations with slightly different I, O, V definitions:

Importance refers to the immediate importance to live safety of the scenario, location and threat.

Occurrence refers to the likelihood of a scenario, location and threat, occurring including:

- General likelihood of threat type being used
- Likelihood of threat being used at the specific location
- Likelihood of specific threat size being used.

Vulnerability is a direct measurement of the casualties caused by the scenario.

Scenario Risk Analysis

For each scenario some components, procedures, and equipment are more critical to life safety in the tunnel than others. A rational and consistent method to assess and compare risk among these variables and judge the effectiveness of varied mitigation schemes is needed to cost-effectively prioritize mitigation measures. This scenario-based comparative process for risk assessment accomplishes this using the following equation:

$$\mathbf{R}_s = \mathbf{I}_s\, \mathbf{O}_s\, \mathbf{V}_s \qquad (6)$$

where:
s = scenario (threat and location)

I_s = Importance of the scenario, s, to the direct life safety of personnel in the tunnel, considering the number of personnel that can be directly or indirectly affected.

O_s = A measure of the relative probability of a basic threat, i, (described below) actually occurring at the given location, j, considering such factors as general likelihood of the threat and visibility/attractiveness of the location as a target.

V_s = A measure of the relative vulnerability of an attack at location, i, given the occurrence of the basic threat, i, and considering access to the location and the potential casualties caused by the threat.

The O and V factors (i.e. O_s V_s) are the result of scenario (*i)* and vulnerabilities from the threats. The basic threats considered are the same as described for the operational out of services risk calculations. Some of the basic threats are not likely to cause casualties in highway tunnels; therefore a subset is proposed for this scenario analysis. The specific threats used for the scenario analysis are:

- Explosive threats, VBIED, of three specific sizes: *x* lb, 2*x* lb, and 8*x* lb.
- Fire threats of three specific sizes: 6*y* MW, 20*y* MW, and 60*y* MW
- Industrial Chemical Spill (ICS) threats from pressurized tanks of three specific sizes: 2*z* gal, 6*z* gal, 70*z* gal, for a lighter than air and heavier than air chemical.

Values of *x*, *y*, and *z* are chosen by the user to provide an appropriate range of threats for the tunnel location.

Importance Factor, I_s

The importance factor measures the importance of an individual scenario location to the safety of the tunnel occupants, considering the number of exposed or at risk population, importance for life safety and providing a survivable environment (protection from hazards and localization of hazards), the importance to emergency evacuation and shelter, and importance for emergency response and rescue (consider safety of responders, time to respond). For example, some tunnel systems, such as ventilation towers serve only part of the tunnel length; and some tunnel systems such as electrical substations have no direct impact on occupants. Damage at these locations, to these systems, or introduction of chemicals to these systems will only affect part of the overall tunnel population. However, people are as important in one location as another. Always use 1.00 for this factor unless there is a specific reason to do otherwise.

The equation for this factor is the same as was used for the operational importance:

$$\mathbf{I}_s = \Sigma\, [\mathbf{wf}_k \bullet \mathbf{a}_{ks}]_s \qquad (7)$$

Importance values for life safety:

- 1.00 = Normal importance to life safety. (Almost always use this value);
- 0.75 = Lower than some other locations;
- 0.50 = Lower than most other locations; and
- 0.00 = Not important to life safety.

Occurrence Factor, O_s

This factor is calculated with Eq. (8).

$$\mathbf{O}_s = \Sigma\, [\mathbf{wf}_k \bullet \mathbf{a}_{ks}]_s \qquad (8)$$

The occurrence factor evaluates the relative likelihood of a basic threat, actually occurring at the scenario location, s, considering the attributes described below. The occurrence factor attributes are subjective and do not represent refined probabilities. Instead, they produce a measure of the subjective expectation that threat *i* will occur compared to the other threats.

The attributes for the occurrence factor are general threat likelihood, threat likelihood at location, and likelihood of threat size.

General Threat Likelihood

This attribute describes the general likelihood that attackers prefer this type of threat compared to others. For example, history has shown that many terrorists prefer VBIEDs over HEIEDs. Even more, very few have chosen non-explosive options, and even fewer have chosen fire or impact. However, for causing casualties, a terrorist will recognize that fires and spills in a closed environment can be effective, particularly because there are numerous examples of casualties and disruptions from accidental tunnel fires.

This attribute will be the same, regardless of the scenario location under consideration. Therefore, the likelihood of a VBIED should be considered independently of the location. The likelihood that the given threat will be used at a given location is covered separately. The values used are the same as described for the operational general threat likelihood calculations:

- 1.00 = very likely
- 0.75 = likely
- 0.50 = somewhat likely
- 0.25 = slightly likely
- 0.00 = not likely

Threat Likelihood at Location

This attribute addresses the likelihood of the scenario location under consideration being feasible and attractive for the terrorist. This should take into account the capability for a given threat to be delivered to the scenario location and the attractiveness of that location, i.e. does the terrorist perceive that this location will cause casualties. For example, a terrorist may think that a VBIED would cause more casualties in the middle of a tunnel as compared to the end.

Access issues are considered here. Threat size is not considered here as that is addressed separately with the “Likelihood of Specific Threat Size” factor. Vehicle Restrictions, operationally controlled and physically restricted, greatly reduce the likelihood for vehicle attacks that use VBIEDs, fire, and chemical attacks. Consider types of vehicles allowed in the tunnel, such as heavy goods vehicles (HGV) and dangerous goods vehicles (DGV). Values used for this attribute are:

- 1.00 = Very likely, HGV and DGV allowed with normal traffic
- 0.75 = Likely, HGV allowed with normal traffic, no DGV
- 0.50 = Somewhat likely, size restrictions, no HGV or DGV
- 0.25 = Slightly likely
- 0.00 = Not likely

Likelihood of Threat Size

Independent from the scenario location, this attribute reflects the likelihood that an attacker will use a specific threat size. This likelihood is similar to the threat size vulnerability factors for the operational risk:

- 1.00 = very likely
- 0.75 = likely
- 0.50 = somewhat likely

- 0.25 = slightly likely
- 0.00 = not likely

The explosive threat (HEIED and VBIED) is defined by the amount of explosives. The values used reflect the probability of that explosive threat size occurring as part of an attack to cause casualties. The values used are the same as for operational s risk calculations:

- 1.00 = catastrophic damage with less than *x* lbs. explosive weight
- 0.90 = catastrophic damage with *x* to 6*x* lbs. explosive weight
- 0.50 = catastrophic damage with 6*x* to 10*x* lbs. explosive weight
- 0.30 = catastrophic damage with 10*x* to 20*x* lbs. explosive weight
- 0.10 = catastrophic damage with 20*x* to 60*x* lbs. explosive weight
- 0.05 = catastrophic damage with 60*x* to 120*x* lbs. explosive weight
- 0.00 = not applicable or can withstand all of the above-mentioned threats

Fire threat size is defined by the Energy Output of the fire in megawatts (MW). The values used reflect the probability of that fire threat size occurring as part of an attack to cause casualties. The values used are the same as listed for the operational risk calculations:

- 1.00 = catastrophic damage with <= *v* MW fire)
- 0.98 = catastrophic damage with *v* to 3*v* MW fire
- 0.95 = catastrophic damage with 3*v* to 6*v* MW fire
- 0.85 = catastrophic damage with 6*v* to 20*v* MW fire
- 0.50 = catastrophic damage with 20*v* MW to 60*v* MW fire
- 0.00 = not applicable or not vulnerable to fire

Industrial chemical spill threat size is defined by the size of containers in gallons. The values listed below reflect the probability of a terrorist acquiring and using that threat size as part of an attack to cause casualties. These are the values for pressurized industrial chemical tanks:

- 1.00 = Small pressurized cylinders
- 0.98 = Multiple Small pressurized cylinders for local delivery and point use *w* gal total
- 0.95 = Single 2*w* gal tanks
- 0.85 = Two or three 2*w* gal tanks
- 0.70 = Chemical in 25*w* to 50*w* gal truck
- 0.50 = Chemical in 50*w* to 70*w* gal truck
- 0.30 = Chemical in 70*w* to 90*w* gal truck
- 0.00 = Not applicable or No Casualties

Vulnerability Factor, V_s

Eq. (9) is used to calculate the vulnerability factor.

$$\mathbf{V}_s = \Sigma\, [\mathbf{wf}_k \bullet \mathbf{a}_{ks}]_s \tag{9}$$

The vulnerability factor is a value based on the casualties caused by the scenario. Casualties can be expected, even with perfect preparation; however, large numbers of casualties are considered unacceptable by the public. Even small vest bomb attacks that are difficult to prevent can cause

15 to 20 casualties, so the vulnerability value assigned for this level of attack should be relatively low. Hundreds of casualties are clearly undesirable, so the vulnerability value assigned for this level of attack should be relatively high. The ranges of vulnerability value assigned should transition between values so that the effects of mitigations can be differentiated. Values used for this attribute are:

- 1.00 = > 1,000*u* Casualties
- 0.90 = 100*u* Casualties;
- 0.85 = 50*u* Casualties
- 0.75 = 25*u* Casualties
- 0.50 = 10*u* Casualties
- 0.15 = *u* Casualties
- 0.00 = Not applicable or No Casualties

Weighting Factors for Attributes, wf_k

The attributes that contribute to the three risk factors (I, O, and V) do not have equal importance to determine casualty risk. Expert opinion and examination have determined that some of the attributes should have a larger effect (weight) on the risk factors than others.

For example, the “threat likelihood at specific location” attribute should have much more weight on the importance factor than the “general threat likelihood” attribute. That attribute is important to differentiate between two components when all other modifying attributes are equal, but it certainly should not carry as much weight as the “threat likelihood at specific location.” The “wf_k” weight factors in Eqs. (7 thru 9) are used to account for these differences.

The factors in Table 2 below were determined by presenting the method to several tunnel experts and adjusting values using their expert input.

Table 2 Casualty Risk Weighting Factors

Occurrence		**Vulnerability**		**Importance**	
General Threat Likelihood	0.10	Resistance to Threat	1.00	Immediate Importance to Life Safety	1.00
Threat Likelihood At Specific Location	0.60				
Likelihood of Specific Threat Size	0.30				
Sum	1.00	Sum	1.00	Sum	1.00

Application for Operational Out of Service Component Risk

This methodology can best be demonstrated using a generic example tunnel to develop attributes, describe scenarios and calculate risk values. Consider the tunnel shown in Fig. 1.

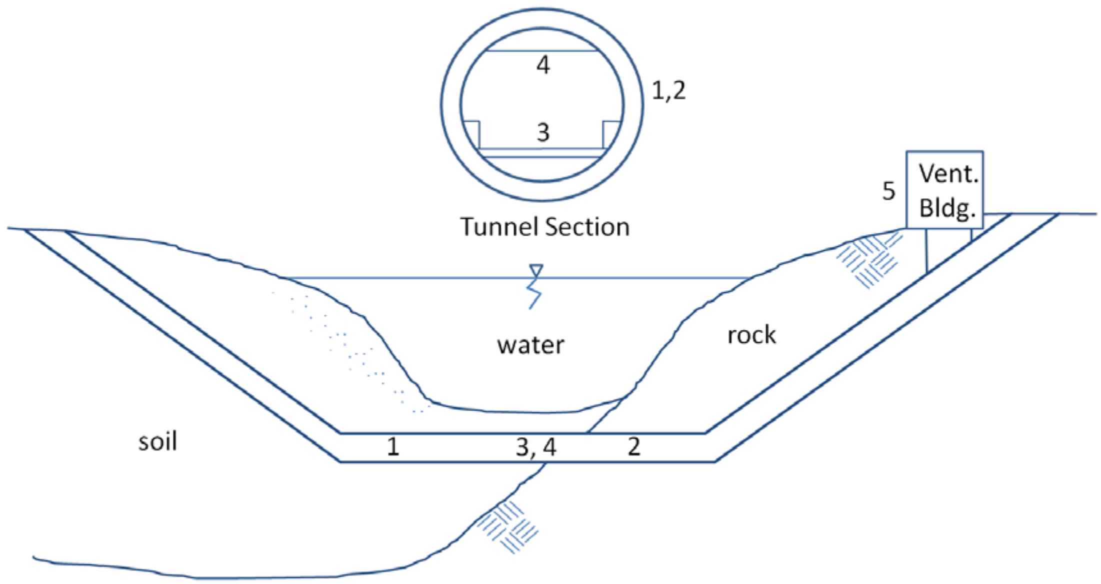

Figure 1 Example Component Risk Analysis

A “baseline” risk assessment is initially conducted for the tunnel in its current condition (i.e., no mitigations). This assessment must include all components that could have an effect on tunnel operations. These components must be identified through a careful study of the tunnel by knowledgeable personnel to identify all potential vulnerable components and locations. A component is defined by the structural member and its specific location. The number of components that may be considered is unlimited. Normally, an assessment of a major tunnel structure would result in 15 or more potentially vulnerable components. However, for simplicity, only the eight components shown in Table 3 will be considered for this example. Note that the order shown is random and has no bearing on the actual risk associated with each component.

Once all components of interest are identified, the individual threat-specific risks for each component are calculated using Eq. (2) and the attribute definition guidelines provided. The component importance factor is threat independent; therefore this value must be calculated only once. The occurrence and vulnerability factors are threat dependent and must be calculated for each threat. This results in quite a few repetitive calculations, making this process conducive to spreadsheet application.

Typical rank-ordered component risk results are shown in Table 4. To avoid providing input to any “terrorist cookbook,” the components are given generic names in Table 4 (i.e., not tied to those listed in Table 3). Note that for the case of eight components and five threats, a total of (8 • 5 = 40) component risk numbers should be shown. However, the risks are very low for some component/threat combinations and they are not shown here to save space.

Table 4 shows the strength of the component level methodology. There is now a ranked listing of components and their specific vulnerabilities, and this provides a quantitative and supportable description of mitigation priorities. With this list, mitigation schemes can be developed along with rough order-of-magnitude costs for each.

For each mitigation scheme, risk should be recalculated using the same methodology and the same components considered for the baseline analysis. These results will provide the end product, a comparison of cost-versus-risk reduction, as shown in Table 4. The cost column could also include life-cycle costs to capture items such as electronic security that will have operational and routine maintenance costs. This would allow for better comparison to one-time cost items such as hardening. Multilevel mitigation schemes may be considered to address different levels of threat. For example, one tunnel liner mitigation scheme may only get the allowable VBIED threat up to *x* explosive weight, whereas another more expensive scheme may raise it up to 5*x* explosive weight. The mitigated risk can be compared to the baseline risk as shown in Table 4.

Table 3 Components Considered in Example: Operational Out of Service Risk Assessment

Component	Location	Figure 1. reference	Threat(s) of concern
1 Tube Wall	Inside submerged tube in soft soil	1	VBIED, HEIED, VI, FIRE
2 Tube Wall	Inside submerged in rock	2	VBIED, FIRE
3 Vent Building	Exterior of ventilation building	3	VBIED, HEIED, VI, FIRE
4 Ceiling / Exhaust Duct	On roadway at center submerged tube	4	VBIED, HEIED, FIRE
5 Floor / Fresh Air Duct	On roadway at center submerged tube	5	VBIED, HEIED, FIRE

Table 4. Components Ranked by Decreasing Base Risk

Component	Threat	Base risk	Mitigated risk	Risk reduction
A	VBIED	0.47	0.10	0.37
B	VBIED	0.45	0.15	0.30
C	VBIED	0.45	0.12	0.33
B	HEIED	0.36	0.15	0.21
C	HEIED	0.36	0.15	0.21
B	FIRE	0.33	0.02	0.31
C	FIRE	0.33	0.22	0.11

Application for Casualty risk

The application of this methodology can best be demonstrated through the generic example tunnel shown in Fig. 2.

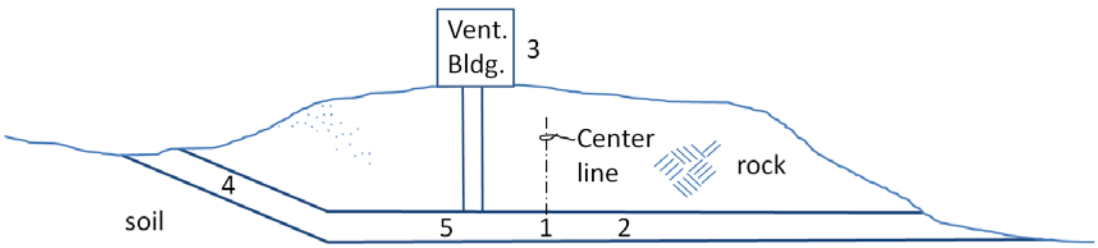

Figure 2 Example Casualty Risk Analysis

A "baseline" risk assessment is initially conducted for the tunnel in its current condition (i.e., no mitigations).

The available combinations of threat types and sizes and locations are unlimited. For the example assessment three threat types of three sizes were placed at 4 critical locations in the tunnel.   An assessment of a major tunnel structure could result in 30 or more potential scenarios. However, for simplicity, only the five scenarios shown in Table 5 will be considered for this example. Note that the order shown is random and has no bearing on the actual risk associated with each scenario.

Once all scenarios of interest are identified, the individual threat-specific risks for each scenario are calculated using Eq. (6) and the attribute definition guidelines. This results in quite a few repetitive calculations, making this process very conducive to spreadsheet application.

Typical rank-ordered scenario risk results are shown in Table 6. To avoid providing input to any "terrorist cookbook," the scenarios are given generic names in Table 6 (i.e., not tied to those listed in Table 5). Note that for the case of three threat types, three threat sizes and four threat locations, a total of (3 • 3 • 4 = 36) scenario risk numbers should be shown. However, the risks are very low for some scenarios, and they are not shown to save space.

Table 6 again shows the strength of the scenario methodology.   There is now a ranked listing of components and their specific vulnerabilities, and this provides a quantitative and supportable description of mitigation priorities. With this list, mitigation schemes can be developed along with rough order-of-magnitude costs for each.

For each mitigation scheme, risk should be recalculated using the same methodology and the same scenarios as for the baseline analysis. These results will provide the end product, a comparison of cost versus risk reduction, as shown in Table 6. . The cost column could also include life-cycle costs to capture items such as electronic security that will have operational and routine maintenance costs. This would allow for better comparison to one-time cost items such as hardening. Multilevel mitigation schemes may be considered to address mitigations to different levels of threat. For example, one evacuation/egress scheme may only get the expected casualties down to 5*x*, whereas another more expensive scheme may get the expected casualties down to *x*. The mitigated risk can be compared to the baseline risk as shown in Table 6.

Table 5 Casualty Attack Scenarios

Scenario	Scenario Description	Figure 2 reference
1	VBIED size 2*x* lbs in center of tunnel	1
2	VBIED size 8*x* lbs at station 12+50 in tunnel	2
3	VBIED size *x* lbs in next to ventilation building	3
4	Fire size 20*x* MW just inside tunnel west portal	4
5	ICS size 6*x* gal, heavier than air chemical at station 2+50 in tunnel	5

Table 6 Risk Comparison

Scenario	Base risk	Mitigated risk	Risk reduction	Mitigation Cost
A	0.47	0.10	0.37	$
B	0.45	0.15	0.30	$
C	0.45	0.12	0.33	$
D	0.36	0.15	0.21	$
E	0.36	0.15	0.21	$

Conclusions

A unique risk-based methodology has been presented whereby tunnel security mitigation strategies can be prioritized for a given structure to fit a limited budget. Based upon recent experience by the authors on several major tunnels, the methodology has proven very useful and provided consistent and supportable results. Though this process requires a lot of data and repetitive calculation, spreadsheet automation and real time practice greatly simplify its application. This is a valuable tool for engineers to develop cost-effective security projects and demonstrate quantitatively the value of security mitigation.

It is useful to recognize that this tool can improve with input from tunnel professionals who use it. Thus, it is the purpose of this paper to present the methodology and stimulate suggestions for its continued improvement. It is also hoped that this tool will add yet one more weapon to the arsenal that we as a nation can deploy in our fight against terrorism.

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