FTA Report No. 0235

FTA RESEARCH
FEDERAL TRANSIT ADMINISTRATION

Research Report and Findings: Review of Specifications and Guidelines for Rail Tunnel Repair and Rehabilitation

PREPARED BY

Anna Rakoczy, Ph.D.
Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads

NOVEMBER 2022

U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

Courtesy of Adobe Stock, Nina Abrevaya, #410711704

Research Report and Findings: Review of Specifications and Guidelines for Rail Tunnel Repair and Rehabilitation

NOVEMBER 2022

FTA Report No. 0235

PREPARED BY
Anna Rakoczy, Ph.D.
Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads
55500 DOT Road
Pueblo, CO 81001

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

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

Metric Conversion Table

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

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE November 2022	2. REPORT TYPE Final	3. DATES COVERED September 2018–May 2019
4. TITLE AND SUBTITLE FTA Standards Development Program: Review of Specifications and Guidelines for Rail Tunnel Repair and Rehabilitation		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Anna Rakoczy, Ph.D.		5d. PROGRAM NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSE(ES) Transportation Technology Center, Inc. (TTCI) A subsidiary of the Association of American Railroads 55500 DOT Road Pueblo, CO 81001		8. PERFORMING ORGANIZATION REPORT NUMBER FTA Report No. 0235
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Transit Administration Office of Research, Demonstration and Innovation 1200 New Jersey Avenue, SE, Washington, DC 20590		10. SPONSOR/MONITOR'S ACRONYM(S) FTA 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

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

13. SUPPLEMENTARY NOTES [www.transit.dot.gov/research-innovation/fta-reports-and-publications] [https://www.transit.dot.gov/about/research-innovation] [https://doi.org/10.21949/1527648] Suggested citation: Federal Transit Administration. FTA Standards Development Program: Review of Specifications and Guidelines for Rail Tunnel Repair and Rehabilitation. Washington, D.C.: United States Department of Transportation, 2022. https://doi.org/10.21949/1527648.

14. ABSTRACT
After the Washington Metropolitan Area Transit Authority (WMATA) L'Enfant Station rail accident in 2015, the National Transportation Safety Board (NTSB) issued two recommendations—1) Recommendation R-16-01: Issue regulatory standards for tunnel infrastructure inspection, maintenance, and repair, incorporating applicable industry consensus standards into those standards, and 2) Recommendation R-16-02: Issue regulatory safety standards for emergency egress in tunnel environments. To effectively respond to NTSB's recommendations, this report was prepared to assist the transit industry in developing standards and/or recommended practices to address Recommendation R-16-02 – tunnel repairs and rehabilitation and includes a condition-based rating system for tunnels as a tool for evaluation for rehabilitation and guidelines for a tunnel inventory database.

15. SUBJECT TERMS
Rail tunnel repair, rail tunnel rehabilitation, transit tunnel repair, transit tunnel rehabilitation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	Unlimited	46	19b. TELEPHONE NUMBER

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abstract

After the Washington Metropolitan Area Transit Authority (WMATA) L'Enfant Station rail accident in 2015, the National Transportation Safety Board (NTSB) issued two recommendations—1) Recommendation R-16-01: Issue regulatory standards for tunnel infrastructure inspection, maintenance, and repair, incorporating applicable industry consensus standards into those standards, and 2) Recommendation R-16-02: Issue regulatory safety standards for emergency egress in tunnel environments. To effectively respond to NTSB's recommendations, this report was prepared to assist the transit industry in developing standards and/or recommended practices to address Recommendation R-16-02 – tunnel repairs and rehabilitation – and includes a condition-based rating system for tunnels as a tool for evaluation for rehabilitation and guidelines for a tunnel inventory database.

This report was prepared for the Center for Urban Transportation Research (CUTR) by Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads, Pueblo, Colorado. It is based on studies conducted by TTCI with the direct participation of (CUTR) to criteria approved by their client, the Federal Transit Administration (FTA). The contents of this report imply no endorsements whatsoever by TTCI of products, services, or procedures, nor are they intended to suggest the applicability of the test results under circumstances other than those described in this report. TTCI is not a source of information with respect to these tests, nor is it a source of copies of this report. TTCI makes no representations or warranties, either expressed or implied, with respect to this report or its contents. TTCI assumes no liability to anyone for special, collateral, exemplary, indirect, incidental, consequential, or any other damages resulting from the use or application of this report or its contents.

Executive Summary

Background

The Center for Urban Transportation Research (CUTR) at the University of South Florida contracted with the Transportation Technology Center, Inc. (TTCI) to research and develop specifications and guidelines for rail transit tunnel maintenance, inspection, repair, and rehabilitation under CUTR's cooperative agreement with the Federal Transit Administration (FTA).

To address the research needs for this project, subject matter experts from the Transportation Technology Center, Inc. (TTCI) performed background research on safety-critical emphasis areas that may be used to support the identification and modification or development of voluntary standards or recommended practices, including those for rail transit tunnel maintenance, inspection, repair, and rehabilitation, through the American Public Transportation Association (APTA) Standards Program. The necessary research and background studies conducted under this project also inform evidence-based safety policy and decision-making (regulations, directives, advisories, etc.) for FTA's Office of Transit Safety and Oversight (TSO), as appropriate.

Context

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

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

To respond to NTSB's recommendations, FTA directed the CUTR research team, which included personnel from TTCI, to perform research to assist APTA in developing voluntary standards or recommended practices for the transit industry for:

- Inspection and maintenance
- Repair and rehabilitation
- Emergency egress in tunnels

Methods

The repair and rehabilitation information reflected in this report was gathered primarily through a literature review. Information from an interactive class related to the National Cooperative Highway Research Program (NCHRP) Report 816[1] is also incorporated in the appendix.

Key Findings

Based on the literature reviewed, the following findings are noted to assist in addressing R-16-02:

- **Finding 1** – The transit industry should consider establishing a rating system, standard evaluation procedures, and a prioritization method for system components, including tunnels. A rating system and condition assessment procedures will provide numerical justification and prioritization for repairs or rehabilitation. A comprehensive prioritization method may consider effectiveness, a risk-based analysis, capital funding, and staffing programs to accomplish tunnel preservation goals and serve as a training tool for new personnel. This finding fulfills National Safety Plan objectives to manage the safety risks and safety hazards within public transportation systems. The finding can also assist transit agencies that receive federal financial assistance[2,3] in implementing TAM for their capital assets used to provide public transportation.
- **Finding 2** – Based on the comparison of two condition assessment methods, NCHRP Report 816 (the latest revision) can be adapted to develop condition assessments for rail transit tunnels. NCHRP Report 816 provides a process for prioritizing needs using an overall measure of effectiveness calculated using a risk-based urgency score and developing capital funding and staffing programs to accomplish tunnel preservation goals. The procedures described in NCHRP Report 816 can be considered along with the *Specifications for National Tunnel Inventory* (SNTI),[4] which contains instructions for submitting the inventory and inspection data to the FHWA. The SNTI is dedicated to highway infrastructure; therefore, it needs to be adjusted for transit applications.
- **Finding 3** – Adapt tunnel inspection and repair methods to transit applications using various sources such as the Federal Highway Administration (FHWA) *Technical Manual for Design and Construction of Road Tunnels – Civil Elements* (AWSD1.1/D1.1) for structural steel repairs, American Association of State Highway and Transportation Officials

[1] NCHRP Report 816, 2015, "Guide for the Preservation of Highway Tunnel Systems," Washington, DC.
[2] FTA National Public Transportation Plan, 2017 edition, Washington, DC.
[3] FTA, *TAM Facility Performance Measure Reporting Guidebook: Condition Assessment Calculation*, March 2018.
[4] FHWA-HIF-15-006, "Specifications for National Tunnel Inventory," 2015 edition, http://www.fhwa.dot.gov/bridge/inspection/tunnel/

(AASHTO) specifications for repair of steel fastening systems, and sources identified in the FTA report *Rail Tunnel Design, Construction, Maintenance and Rehabilitation* (to be published). This would provide standards or recommended practices identifying, characterizing, and repairing typical defects in transit tunnel systems.

Section 1 Background

Transportation Technology Center, Inc. (TTCI), contracted by the Center for Urban Transportation Research (CUTR) at the University of South Florida, was tasked by the Federal Transit Administration (FTA) to research and develop specifications and guidelines for rail transit tunnel maintenance, inspection, repair, and rehabilitation.

To meet the research needs for this project, subject matter experts from TTCI performed background research on safety-critical areas that may be used to support the identification and modification or development of voluntary standards or recommended practices, including those for rail transit tunnel maintenance, inspection, repair, and rehabilitation, through the American Public Transportation Association (APTA) Standards Program. The necessary research and background studies conducted under this project also inform evidence-based safety policy and decision-making (regulations, directives, advisories, etc.) for FTA's Office of Transit Safety and Oversight (TSO), as appropriate.

Context

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

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

To respond to NTSB's recommendations, FTA directed the CUTR research team, which includes CUTR and personnel from TTCI, to perform research to assist APTA in developing voluntary standards or recommended practices for the transit industry in three specific areas:

- Tunnel inspection and maintenance
- Tunnel repair and rehabilitation
- Emergency egress in tunnels

Project Scope

A literature review was performed to identify rehabilitation elements that could be applied to transit tunnels or that need to be created or modified for transit tunnels, including the required modifications. Specific items covered in this report include the following:

- Current industry practice of repair and rehabilitation
- Review of available documents for tunnel rehabilitation, including the FTA *Transit Asset Management (TAM) Guidebook* and National Cooperative Highway Research Program (NCHRP) Report 816, "Guide for the Preservation of Highway Tunnel Systems"
- Review of existing condition assessment methods, including scale rating, importance weights, cost-effectiveness, risk-based analysis, and prioritization
- Information about how the condition assessment can be used for prioritizing rehabilitation projects

Section 2

State of the Industry Based on Literature Review

When evaluating tunnel condition state and appropriate repair, it is important to understand tunnel age and transit agency current practices, as these elements can significantly influence tunnel maintenance or rehabilitation. According to survey results published in "Review of Specifications and Guidelines for Rail Tunnel Design, Construction, Maintenance, and Rehabilitation" (P-18-008),[5] 17 of 37 surveyed transportation agencies indicated they own at least one tunnel, with 102 tunnels owned by these 17 agencies.

The data collection survey results revealed a wide range of tunnel construction dates, with three tunnels built in the 1800s and six currently under construction. Of the 102 tunnels, 49 were more than 50 years old, suggesting an aging infrastructure and potential difficulty in retrofitting to the current best practices. In total, 20 U.S. rail transit tunnels have been fully or partially rehabilitated.

The survey also showed that two public documents, the Federal Highway Administration (FHWA)/FTA *Road and Rail Tunnel Maintenance and Rehabilitation Manual*[6] and the *FHWA Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual*,[7] are used widely across the industry. Some transit agencies also have developed their own manuals. The survey results are shown graphically in Figure 2-1.

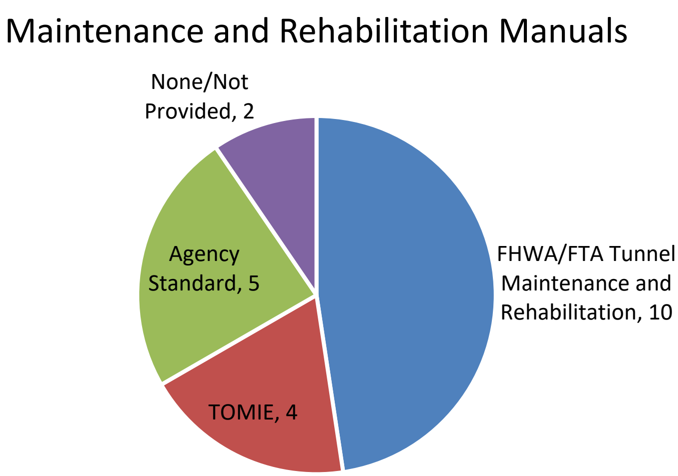

Figure 2-1 *Number of transit agencies that use specific tunnel maintenance and rehabilitation manuals*

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

[6] FHWA and FTA, (2015), FHWA/FTA 2005, *Highway and Rail Tunnel Inspection Manual*, Washington D.C.

[7] FHWA, 2015, FHWA-HIF-15-005, *Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual*, Washington D.C.

Tunnel Repair Practices Based on Literature Review

An ongoing challenge of tunnel inspection and maintenance is that transit agencies do not have alternate routes; thus, shutting down tunnels for inspection or maintenance causes major network disruptions. As a result, inspection and maintenance activities have limited time windows and usually must be completed at night during non-revenue hours. This restrains the time and capabilities for large-scale projects and applies to most transit tunnels.

Tunnel inspections result in substantial benefits by enhancing the safety of the traveling public and protecting investments in key infrastructure. Repairs or changes resulting from inspections could lead to significant economic savings.[8] After each inspection, action items are considered for maintenance and repairs. Actions requiring small budgets and occurring repeatedly or with regular frequency are considered routine maintenance and covered in FTA's *Rail Tunnel Design, Construction, Maintenance and Rehabilitation* (to be published). Findings and associated action items that are complex usually require larger budgets and will be included in a larger-scale repair/rehabilitation project.

Structural repairs generally consist of reinforcing existing steel beams and column elements via addition of structural steel sections (plates, angles, channels, etc.) and restoring concrete elements by removing loose/deteriorated concrete and installing new concrete or patching spalls with various mixtures of repair mortar. New materials used for structural repair are similar to, and generally compatible with historical materials (primarily structural steel and concrete). New steel is generally of higher strength than historic steel. Likewise, new concrete combined with additives is currently used to enhance durability, control shrinkage, and facilitate placement in remote and difficult-to-access locations.

In addition, the *TOMIE Manual* presents various structural repair methods to reinstate the structural capacity of a deteriorated tunnel liner, including methods for demolition of unsound concrete, brick, or steel, and restoration of the tunnel liner to its original condition and function. Details for the repair of concrete, steel reinforcement, and embedded elements of the tunnel liner system are provided in the manual. In this report, repair methods from the manual are presented for structural bonding of cracked concrete, components of segmental liners, steel/cast iron components, brick, dimension (Ashlar) stone, and concrete masonry elements that exist in many tunnel systems.

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

Groundwater Intrusion

The most significant problem found during tunnel inspections is groundwater intrusion. The presence of water in a tunnel, especially if uncontrolled and excessive, accelerates corrosion and deterioration of the tunnel liner and may cause electrical power system grounding and arcing events. An example of leakage and corrosion on a beam is presented in Figure 2-2.

Figure 2-2 *Example of leakage and corrosion on a beam (view from station)*

FHWA's *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*[9] is the primary resource that focuses on the identification, characterization, and repair of typical structural defects in a tunnel system. It identifies the methods for measuring the flow of water from a leak, describes proper methods for identifying the types of remedial action to be taken, and describes the procedures to install various types of grout.

Groundwater intrusion can be mitigated by treating the ground outside the tunnel or sealing the inside of the tunnel. The key to a successful leak containment program is the selection of the proper repair products, which account for the degree of leakage into the tunnel from the defect.

Typically, tunnel defects that cause leakage are deficiencies in construction joints, liner gaskets, and cracks extending through the liner's full depth. Common repair methods are as follows:

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

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

For joints that move, only chemical grout is appropriate. Joint or crack movement will fracture any particle grout and cause the leak to reappear.

In situations in which the defect is not subject to movement and is dry at the time of repair, an epoxy grout can be injected into the defect in the same manner that concrete is structurally re-bonded. Particle grouts often are used for outside of the tunnel liner or in very large dry cracks and joints. Polyurethanes and acrylates are the most commonly used grouts for sealing cracks in tunnel liners. Many typical grouts for injecting into cracks and joints in a tunnel liner can be found in the FHWA report.[10]

Structural Repair – Concrete

Repair of concrete delamination and spalls in tunnels (Figure 2-3) has traditionally been performed by the form-and-pour method for the placement of concrete or by the hand application of cementitious mortars that have been modified by the addition of polymers. Today, the repair of concrete structural elements is performed typically by two methods:

- Hand-applied mortars for small repairs
- Shotcrete for larger structural repairs

[10] *Ibid*.

Figure 2-3 *Example of spalling concrete from tunnel ceiling*

Shotcrete is the pneumatic application of cementitious products to restore concrete structures. The American Concrete Institute defines shotcrete as a "mortar or concrete pneumatically projected at a high velocity onto a surface." Over the years, developments in materials and application methods have made the use of polymer cementitious shotcrete products for repairing tunnel liner defects in active highway tunnels cost-effective. The selection of the process type and the material to be applied depends on the specific conditions for tunnel access and available time for repair installation. Shotcrete is preferred to other repair methods since the repair is monolithic and becomes part of the structure. Using shotcrete allows for rapid setup, application, and ease of daily transport into and out of the tunnel.

Structural Injection of Cracks

Cracks that are no longer moving and that occurred due to structural movement (e.g., settlement) should be structurally re-bonded. Any crack being considered for structural re-bonding must be monitored to assess if any movement is occurring. Structural analysis of the tunnel lining should be performed to ascertain if the subject crack requires re-bonding.[11]

Three types of resin are typically available for injection of structural cracks in tunnels—vinyl ester resin, amine resin, and polyester resin. Amine and polyester resins are best-suited for the structural re-bonding of tunnel cracks. Both resins are unaffected by moisture during installation and will bond saturated concrete surfaces. Vinyl ester resin will only bond to completely dry concrete surfaces and does not structurally re-bond moist cracks or saturated concrete.

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

Segmental Lining Repair

The most common problems with segmental cast-iron and steel liners are the deformation of the flanges and corner spalling of precast concrete segments. These problems occur at installation or because of impact damage from installation construction machines. In addition, the rusting through of the liner plate of steel/cast iron segments occasionally occurs.

- *Precast concrete segmental liner* – Repairing spalls in precast concrete liner segments is performed using a high-performance polymer-modified repair mortar, which is formed to recreate the original shape of the segment. If the segment gasket is damaged, the gasket's waterproofing function is restored by the injection of a polyurethane chemical grout, as described above. Damaged bolt connections in precast concrete liner segments are repaired by carefully removing bolts and installing new bolts, washers, waterproof gaskets, and nuts. The bolts are torqued, and a quality assurance (QA) process used to match original specifications.
- *Steel/cast iron liner* – The repair of steel/cast iron liners varies according to the type of liner material. Common defects in these liners are deformed flanges and penetration of the liner segment due to rusting. Deformed flanges can be repaired by reshaping the flanges with hammers or heat. Holes in steel liner segments can be repaired by welding on a new plate. Bolted connections often have galvanic corrosion caused by dissimilar metal contact and usually require replacement of the entire bolted connection. When the bolted connection is replaced, a nylon isolation shoulder washer is used to prevent contact between the high-strength bolt and the liner plate. Repairs to cast iron liner segments are similar to those for steel. However, since cast iron (and steel made before 1923) cannot be welded, the repair plate for the segment is installed by brazing the repair plate to the cast iron or by drilling and tapping the liner segment and bolting the repair plate to the original liner segment. In some instances, it is easier to fill the area between the flanges with shotcrete or polymer-modified shotcrete.

Steel Repair

Structural steel is commonly used at tunnel portals in support of internal ceilings, in columns, segmental liners, and equipment fixations, and as standoffs for tunnel finish treatments. The most recent version of the American Welding Society's Standard Structural Steel Welding Code *AWSD1.1/D1.1 Structural Welding Guide* should be used for welded steel connections. Repairs to rivets and bolting must comply with American Association of State Highway and Transportation Officials (AASHTO) specifications. Corrosion of steel components should be evaluated to confirm that capacity is not compromised. In case of severe corrosion (Figure 2-4), replacement of the corroded component may be the only option.

Figure 2-4 *Example of deteriorated steel columns*

Masonry Repair

The restoration of masonry linings composed of clay brick or Ashlar (dimension) stone consists of repointing deficient mortar. Repointing of masonry joints involves raking out the joint to a depth of approximately 1 in. (2.54 cm). After the joint has been raked and all old mortar removed, material consistent with the base material is used for repointing. This material may be a cementitious mortar or a cementitious mortar fortified with an acrylic bonding agent.

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

Unlined Rock Tunnels

Unlined rock-lined tunnels do not require a permanent concrete, brick, or steel lining, as the rock was determined to be of sufficient strength with minimal reinforcement. These tunnels also are usually short in length. Most have support systems consisting of various types of rock reinforcement, including rock dowels, rock bolts, cable bolts, and other reinforcements, that were placed at various angles to cross rock mass discontinuities.

Rock reinforcement elements may deteriorate and lose strength due to exposure to typical corrosive tunnel environments and require installation of new rock reinforcement elements. Replacing rock reinforcement elements requires a detailed investigation of the tunnel's structural geology by an engineering geologist or geotechnical engineer with experience in geologic mapping and rock stability analysis.

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

Special Considerations for Supported Ceilings and Hangers

Suspended ceilings are generally supported by keyways in the tunnel walls and hanger rods attached to the tunnel liner either by cast-in-place inserts or post-installed mechanical or adhesive (chemical) anchors. FHWA issued a Technical Advisory in 2008[12] strongly discouraging the use of adhesive anchors for permanent sustained tension or overhead applications. Any adhesive anchors in road tunnels must conform to current FHWA directives and other applicable codes and regulations.

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

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

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

[12] https://www.fhwa.dot.gov/bridge/t514034.pdf.

Rehabilitation Practices Based on Literature Review

The primary purpose of structural rehabilitation is to restore structural elements (steel/concrete—beams, columns, ceilings, and walls) to a state of good repair and to protect against future deterioration. Tunnel rehabilitation may also be performed to upgrade the tunnel to meet higher specifications or repair unacceptable tunnel performance to ensure proper serviceability. Rehabilitation is the costliest level of repair, so it is important to fully understand the economic impact of tunnel maintenance in preventing the need for rehabilitation. Two FTA documents provide methods for evaluating the decision to rehabilitate.

In 2018, FTA published the *Transit Asset Management (TAM) Guidebook* that details transit agency methods in measuring and reporting facility condition assessments to the National Transit Database (NTD).[13] The Transit Economic Requirements Model (TERM) scale uses a five-point evaluation scale. FTA's TERM Condition Assessment rating scale is described in more detail in a parallel report on tunnel inspection (*Highway and Rail Transit Inspection Manual* superseded by the *TOMIE Manual*).[14]

In TERM, an asset is deemed to be in good repair if it has a rating of 3, 4, or 5; a facility is deemed to not be in good repair if it has a rating of 1 or 2. The TAM rule is required for all assets but does not require a specific method for conducting asset condition assessments. The *TAM Guidebook* covers administrative and maintenance facilities but does not cover transit tunnels.

The other document that can be used as a guideline is the NCHRP Report 816, "Guide for the Preservation of Highway Tunnel Systems," which presents a guide for the preservation of highway tunnel systems that can be adapted by transit agencies. It provides a process using an overall measure of effectiveness calculated using a risk-based urgency score to prioritize needs and develop capital funding and staffing programs to accomplish tunnel preservation goals. Report 816 can serve as a training tool for new personnel.

Condition Assessment Calculation using TAM

The TAM rule at 49 CFR Part 625, Subpart D – Performance Management established performance measures to be reported to the NTD Asset Inventory Module (AIM). This guidebook outlines the calculation of the Facility Condition Assessment for reporting to the NTD. In addition to AIM reporting, the TAM rule requires asset inventory and asset condition assessments at a level of detail

FTA, 2018, *TAM Facility Performance Measure Reporting Guidebook*, Condition Assessment Calculation.
FHWA, TOMIE Manual, *op. cit*.

sufficient to monitor and predict the performance of assets and to inform investment prioritization in the TAM Plan. Facility condition assessments assess the condition of and assign a rating to facility assets using FTA's TERM scale. The guidebook provides procedures for complying with the condition assessment requirement.

Steps to assess and report facility conditions and performance measures are the following:

Step 1 – Identify facility type and rating levels.
Step 2 – Conduct assessment.
Step 3 – Aggregate results.
Step 4 – Calculate performance measures.
Step 5 – Document and report.

Step 1 is covered in more detail in a parallel report on the *TOMIE Manual*.[15]

The condition measure used in the NTD is the five-point scale used by FTA's TERM (Table 2-1). Transit agencies must use this scale to report the condition of their facility assets.

Table 2-1 *FTA TERM Condition Assessment Scale*[16]

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

Condition Assessment

The condition assessment is primarily intended to assess the overall physical condition of the facility to support capital investment decisions. However, any defects that may constitute a safety concern or potential service delay may require immediate attention. Primary level ratings with a portion or all of their secondary levels assigned a rating of 1 (poor) may have issues warranting a structural or detailed review.

[15] FHWA, FHWA-HIF-15-005, *op. cit*.
[16] FTA, TAM Guidebook, op. cit.

Prior to a facility condition assessment, it is recommended that the inspector gather and review the results of any previous inspections as well as the following:

- Agency procedures – Review inspection and maintenance procedures, including how they have been followed or updated in the past.
- Inspection schedule – Understand how the inspection schedule aligns with the reporting schedule discussed in the first part of the TAM guidebook.
- Data needs – Review applicable fields in the AIM and, when relevant, review these during the inspection process.
- Warranty status and any additional information on the age of the facility and building materials; this may clarify useful life and obsolescence.
- Any other known issues, such as whether the asset has been built to current standards. Inspectors are required to review the results of previous inspections and records of past defects found and/or corrected.

This information provides useful background to the survey of the facility's condition, revealing if work has recently taken place, recently been identified, or needs have already been met, identified, or deferred. These documents also may reveal areas that require more careful review during the inspection process.

Agencies may choose how to weigh their secondary levels when aggregating to the primary level rating. Agencies are expected to develop and document a methodology for aggregating ratings for a given facility.

Aggregate Results

After the conditions of individual facility levels are assessed and aggregated, the next step required to support NTD reporting is to calculate an overall condition rating for each facility and then the overall performance measure for each of the two facility groups—the administrative and maintenance group and passenger and parking facilities group.

It is important to use a consistent, repeatable method for this calculation, and there are several conventions used in similar applications. The following sections describe alternative approaches to aggregating primary and secondary level condition data into a single overall value for facility condition. Provided an agency has sufficient data, the recommended approach to calculate a weighted average condition rating is Alternative 1. However, an agency may use any of the approaches described below.

Alternative 1: Weighted Average Condition

This approach requires using known replacement costs. Given these replacement costs, the average rating is calculated for each primary level as described below. An overall rating is calculated by weighting each primary and secondary level rating by the replacement cost. The specific steps in the calculation are as follows:

- Step 1. Calculate the average rating of facilities using the primary level TERM scores and their respective replacement costs. To calculate the condition rating, take the sum of each primary level TERM score multiplied by its respective replacement cost, and divide the total by the sum of all replacement costs (weights). The aggregated facility condition rating is calculated as follows:

  $$FR = \frac{\sum_i CR_i CW_i}{\sum_i CW_i}$$

  where *FR* is the overall facility rating, CR_i is the TERM score for rating level i, and CW_i is the weighted, or replacement cost, for rating level i.

  – Weighting – Replacement costs should be the only method of weighting for the weighted average condition approach as it is expected that agencies will have an understanding of their assets at the primary level.

- Step 2. Round off the overall rating value for the facility to the nearest integer value and report the integer condition rating to NTD. If the fractional portion of the rating is less than 0.5, the rating would be rounded down; if it is 0.5 or greater, it would be rounded up.

Alternative 2: Median Value

If an agency has limited data on replacement costs, an alternative approach for calculating the overall condition rating of a facility is to use the median value of all primary or secondary rating levels. The median value is the middle value in a series of sorted numbers. The specific steps in the calculation are as follows:

Determine the condition rating of each level and then sort the TERM scores in ascending order. When there is an odd number of values, the median is the value that falls in the middle of the list. When there is an even number of values, choose the lower of the two middle values since that is the condition rating that at least 50 percent are at or below. For example, if 50 percent of the secondary level have a TERM rating of two, 30 percent have a TERM rating of three, and 20 percent have a TERM rating of four, then the aggregated rating would be two, as over half of the secondary level have a rating of two or less. Note that the median, in this case, is not an average or mean value, meaning that each number’s individual value is not considered.

Alternative 3: Alternative Weighting

An agency may use an alternative approach provided the approach is consistent, repeatable, and yields a single value for each facility using the five-point TERM condition scale. For example, an agency may prefer to calculate a weighted average condition, such as that illustrated in Alternative 1, but lacks sufficient data on replacement costs. Instead, an agency may compute a weighted average condition, weighting each level by a factor that serves as a proxy for asset value, or develop a measure of criticality, which could be used as a weighting factor.

Equal weighting is another option for agencies; as the name implies, each secondary level would be weighted equally. The equal weighting approach is not recommended for the primary level. If an agency chooses such an alternative approach, the calculation approach and rationale for its use must be documented. These techniques also may be used to calculate the primary level rating after inspecting each secondary level of the asset. While not reported to NTD, ratings must be retained in the event an agency changes its aggregation approach and needs to recalculate previously-reported conditions.

Calculate Performance Measures

After determining the overall facility ratings for each of its administrative and maintenance items and passenger and parking facilities items, an agency must calculate the performance measure for each of the overarching facility groups:

- Administration and maintenance facilities
- Passenger and parking facilities

To determine the performance measure for a facility category (i.e., administrative and maintenance; passenger and parking), count the number of facilities in that category with a rating below three and divide the value by the total number of facilities in the facility category (e.g., passenger and parking). Note that the performance measure is the minimum each agency is required to report. Grantees are invited to expand upon this requirement as part of their TAM plan.

Reporting (5.0)

The *NTD Policy Manual* lists requirements for collecting and reporting financial, inventory, service, and safety data for transit agencies that receive 49 U.S.C. §§ 5307 and 5311 funds.

Condition Assessment Calculation using NCHRP 816

NCHRP Report 816[17] provides a process, using an overall measure of effectiveness that is calculated using a risk-based urgency score, to prioritize needs and develop capital funding and staffing programs to accomplish tunnel

[17] NCHRP Report 816, *op. cit.*

preservation goals. This NCHRP report can be a resource for RTAs to use to train new personnel on performing condition assessments. The material in this NCHRP report will be of immediate interest to tunnel owners and operators.

As with other U.S. infrastructure funding, highway and railway tunnel preservation and improvement funding is limited. Multiple agencies and, frequently, multiple departments within an agency compete for available funding. Tunnel needs must be weighed against the other asset preservation needs and prioritized based on the entire agency's goals and objectives.

As the survey results noted previously, many tunnels in the U.S. are decades old. Tunnels built decades ago most likely were not designed to current fire and life safety standards, so significant ventilation and electrical system upgrades may be needed.

Asset Management Framework

Tunnel preservation includes actions or strategies that prevent, delay, or reduce deterioration of tunnels or tunnel systems; restore the function of existing tunnels; keep tunnels and their systems in good condition; and extend their lives. Tunnel preservation may include preventive maintenance, cyclical preventive maintenance (activities on a predetermined interval), condition-based preventive maintenance, and rehabilitation. An asset management process can help prioritize tunnel preservation actions or rehabilitation projects.

Tunnel preservation asset management includes the following steps:

Step 1. Identify agency Level of Service (LOS) (goals and objectives) and the relevant importance of each. Establish an Agency Asset Management Team (AAMT) to identify goals and objectives for the overall transportation system. Goals for tunnel performance may vary slightly from those of the overall transportation system; an agency can select goals for the overall transportation network or tailor goals for its tunnels.

Step 2. Develop tunnel performance measures (targets) for each recommended LOS category. Performance measures provide a means of evaluating how well the overall goal is being achieved by evaluating the performance in a specific area. Each year, and as conditions warrant, the agency can decide if its current performance measures are effective and should continue to be tracked during subsequent years or if performance measures should be modified.

Step 3. Summarize tunnel preservation actions based on condition inspection and regulatory requirements. During inspections, the inspection team notes and documents deficiencies. Recommendations for improvements to remedy deficiencies are typically developed as a part of the inspection process but may also be identified through normal operations.

Step 4. Develop an LOS score for each tunnel preservation action. Each agency will have its own specific LOS scores. The LOS score helps tunnel owners rate preservation actions to better achieve their overall LOS goals.

Step 5. Develop a Cost-Effectiveness (CE) score for each tunnel preservation action. Life cycle costs are calculated for each preservation action and used to evaluate alternative approaches for upgrades and repairs. Costs for each preservation action should include additional maintenance that could be incurred due to delay in rehabilitating or replacing a system or element, as well as the potential savings, such as energy savings resulting from the use of energy-efficient equipment.

Step 6. Develop a Risk-Based Urgency (RBU) score for each tunnel preservation action. The urgency of the preservation action is evaluated using an RBU score, which considers the condition, remaining life, and risk if the action is not implemented, as well as the need for the preservation action in terms of regulatory compliance.

Step 7. Determine weighted percentage for LOS score, CE score, and RBU score.

Step 8. Calculate the overall Measure of Effectiveness (MOE) score for each tunnel preservation action. The combination of three scores (LOS, CE, and RBU) provides the overall MOE as the indicator in establishing the priority for each preservation action.

Step 9. Implement prioritized tunnel preservation action in updated capital plans. To establish the final priority of preservation actions, the tunnel owner reviews the prioritized actions and modifies them as needed, considering the overall system needs and operations, to establish the final priority of preservation actions. The agency schedules preservation actions based on anticipated funding levels to be received in accordance with the agency's capital plans or establishes the future capital plan incorporating the desired preservation actions for each year. The agency establishes staffing needs based on anticipated funding and the specific needs for the preservation actions to be implemented each year. Staffing needed to implement the preservation actions may be procured through external contracts or the hiring of new agency personnel.

Step 10. Evaluate performance (and return to Step 2).

Measuring Effectiveness of Preservation Actions

Several factors must be considered to evaluate the effectiveness of a proposed tunnel preservation action. First, what effect does the improvement have on achieving the agency's overall goals and objectives (i.e., meeting their LOSs)? Second, how cost-effective is the improvement (e.g., does it reduce maintenance or energy costs, what is the ultimate cost per user, and what effect does it have on the remaining life of the asset)? And finally, what are the associated risks if the improvement is delayed, and how urgently is the improvement needed?

The 2011 *AASHTO Transportation Asset Management Guide* provides an approach for risk assessment where the following are evaluated:

- Likelihood of an extreme event, such as a flood, earthquake, asset failure, or other risk drivers, expressed as a probability, or range of probability, of an event.
- Consequences to the asset—a categorization of the asset's damage or loss of function and conditions on occurrence of an event.
- Effect on mission, life, property, and the environment: a categorization of the effect on the agency, the public, users, and non-users of the asset's damage or loss of function caused by the extreme event.

The summary of risk likelihood and consequences are presented in Table 2-2.

Table 2-2 *Risk Likelihood and Consequence Categories*

Likelihood	Consequences				
	Insignificant	*Minor*	*Significant*	*Major*	*Catastrophic*
Very rare	Low	Low	Low	Moderate	High
Rare	Low	Low	Moderate	High	High
Seldom	Low	Moderate	Moderate	High	Extreme
Common	Moderate	Moderate	High	Extreme	Extreme
Frequent	Moderate	High	High	Extreme	Extreme

In addition to assessing risk likelihood, the AAMT will need to set relative weights for each LOS selected as part of determining an LOS score. The NCHRP report describes six general LOS standards that many transportation agencies are using as part of an asset management process. The tunnel owner may decide that all six are valid for its analysis, may select a reduced number, or may add others as it deems necessary. For setting percentages, the AAMT sets rankings in general order of importance from highest to lowest among the LOS standards for the tunnel at the time of the ranking. Examples of LOS weights are presented in Table 2-3.

Table 2-3 *Example of LOS Weights*

LOS	Description	Weight (%)
Safety	Is there a safety concern such that the likelihood exists for fatalities, injuries, or property damage to occur when using the tunnel in its current condition? Do safety concerns exist for the traveling public or for agency personnel and contractors?	40
Reliability	Will the current condition result in a failure that would require lane closures or the need to close the tunnel for a period of time? Does the tunnel have to be shut down to make improvements? Will there be a significant traffic impact during construction? Do traffic volumes using the tunnel result in congestion and backup of traffic during high-usage days?	20
Preservation	Will the tunnel be able to function in the future or are there latent conditions that are likely to cause future problems? Does the remaining life of the asset increase as a result of the preservation action?	18
Quality of service	Do users experience comfortable travel in terms of a smooth riding surface, visibility from adequate lighting, aesthetics (cleanliness of tiles, metal panels, or exposed surfaces) and environment (no leaks from groundwater penetration)?	15
Security	Are there any security concerns with respect to either technological (chemical, biological, radiological, nuclear, explosives, sabotage) or natural hazards (fires, seismic activity, floods, collapses, vehicular accidents) in the tunnel itself or in adjacent facility structures?	5
Environment	Are there environmental concerns, such as the potential for hazardous spills within the tunnel, that could affect the environment within and adjacent to the tunnel?	2

Table 2-3 presents an AAMT evaluation team example that reflects the long-term strategic direction of this individual highway agency. The team considered the following factors:

- **Safety** was the top factor based on the accidents that occurred at a few of the agency's tunnels; the seasonal snow accumulations cause safety concerns at those tunnel entrances in the colder climates; current pavement surface conditions, such as rutting, could cause safety concerns within the travel lanes; and visibility affected by contrasting light levels at all tunnel entrances in the daytime could be improved for better eye adjustment when entering the tunnels.
- **Reliability** was deemed the second most critical factor. This resulted from a series of unexpected events causing tunnel closure for a significant period. The agency's tunnels carry high traffic volumes, and tunnel closure will affect the public due to the length of detours that may be needed or the congestion on other highways where traffic is routed.
- **Preservation** was ranked third because maintaining a state of good repair implies that preservation actions need to occur. Fans nearing the end of their useful life require extensive maintenance/repairs to keep the ventilation system operational. Water infiltration within the tunnel is causing the tiled surface to delaminate and spall, exposing the structural reinforcing in many areas.

- **Quality of service** was ranked fourth because customers complained about the light levels present when they entered the tunnels and infiltrated groundwater dripping onto their vehicles when traveling through them. In addition, ride quality was reduced due to poor roadway pavement conditions, and tunnel aesthetics degraded as tunnel walls were dirty, stained, and needed to be cleaned to improve reflectivity and overall appearance.
- **Security** was ranked fifth because security measures are already scheduled for implementation due to a security breach that recently occurred in a nearby facility. The security systems currently installed are obsolete and in need of replacement. In addition, the agency has received increasing numbers of special requests for moving hazardous/explosive materials through the tunnel during non–rush hours. While security is important, scheduled improvements make security less important than the other LOS standards.
- **Environment** was ranked sixth, as there have been few threats to the environment from the agency's tunnels. Possible environmental concerns might include spills within the tunnel draining to local streams, tunnel emissions exhausting in an urban area with air-rights structures, or disposal of tunnel lights containing hazardous materials. However, the agency deemed the likelihood of these kinds of issues in its tunnels to be low.

This iterative process for ranking consideration should continue within the AAMT until all members agree with the ranking of LOS elements in order of importance.

The ratings are based on the subjective judgment of the tunnel owner trained inspectors and tunnel maintenance personnel. Each rating is intended to capture the degree to which the improvement contributes to the overall agency goals and objectives. Transit agencies may have different agency goals and objectives than highway agencies; however, the steps for conditions assessment will be the same.

Calculating the LOS Score

The aggregate LOS score can be calculated using a weighted sum of the individual scores. The LOS score provides a measure of how well the preservation action would improve or help to achieve the agency's LOS. The LOS score is calculated as follows:

$$LOS = (W_R \times R + W_{Sa} \times S_a + W_{Se} \times S_e + W_P \times P + W_Q \times Q + W_E \times E) / 5$$

Where,

LOS = agency level-of-service score
R = reliability rating
S_a = safety rating
S_e = security rating
P = preservation rating
Q = quality of service rating
E = environment rating
W_R, W_{Sa}, W_{Se}, W_P, W_Q, W_E = weights for reliability, safety, security, preservation, quality of service, and environment scores, where $(W_R + W_{Sa} + W_{Se} + W_P + W_Q + W_E) = 100$

There is a significant degree of subjectivity in the assignment of individual weights and the LOS ratings that are the basis of the LOS score. The weights assigned to each LOS will significantly affect the resulting LOS score and, therefore, should be established by the AAMT and used consistently.

Cost-Effectiveness

Cost plays a significant role in the comparing tunnel maintenance and repair actions and prioritizing actions for implementation. Tunnel owners often will implement the least expensive improvements because they fit within the overall budget, and numerous improvements can be completed versus a few larger, more costly improvements. Sometimes contracting restrictions allow work within a specific dollar limit to proceed more expeditiously than more costly improvements.

Life-cycle costing is typically used to compare alternatives since it allows initial costs to be tempered by potential savings in maintenance and energy over the asset's life. Tunnel assets, however, have varying service lives. Therefore, a means to compare life-cycle costs (LCCs) is to calculate the total LCC over a common period, such as 50 years. Alternatively, the LCC could be annualized over the service life to compare the costs per year.

Implementing the Most Urgent Improvements

When evaluating tunnel preservation priorities, the most urgent improvements should receive higher priority. Risk is an essential factor in determining these priorities. The risk associated with doing nothing (i.e., not implementing the preservation action) could result in an unsafe condition or a condition requiring the closure of the tunnel. Several factors contribute to urgency: condition, remaining life, regulatory requirements, and unplanned events.

The urgency of a preservation action requires careful consideration of the previously noted factors. The associated risks of not implementing the improvement need to be contemplated for each of these factors. There is no simple formula to combine all of these factors; each tunnel may have different risks based on location, physical geography, original construction, age, etc. Therefore, a means of considering these factors to obtain the RBU ratings and score is needed. Risk factors versus urgency and RBU ratings are presented in Table 2-4.

Table 2-4 *Assigning RBU Ratings*

Risk Factors	Urgency	RBU Rating
At least one area suggests the need for immediate action.	Extreme	10
Multiple areas of consideration are of concern, or one area of concern is highly probable and would have significant impact on the LOS.	High	9
		8
		7
At least one area of consideration is of concern.	Medium	6
		5
		4
No areas of consideration are considered critical.	Low	3
		2
		1
No indication of urgency.	Nonexistent	0

Measure of Effectiveness (MOE)

MOE is used as the indicator in establishing the priority of implementing preservation actions. The MOE for a proposed preservation action is calculated by combining the LOS score, the CE score, and the RBU score. It is based on a scale of 0 to 100 and provides a rational means to prioritize a diverse list of preservation actions. The three scores can be weighted differently based on the agency's objectives and overall goals. This is another opportunity to customize the metric for a specific agency and its tunnel assets. The AAMT should establish the weights to be applied to the three individual scores considering its tunnels and overall agency goals and objectives.

Prioritization of Preservation Actions

Prioritization and programming for the next 5-10 years require consideration of many other factors. Sometimes, lower-priority activities will be performed sooner because of their relatively low cost and ability to fit within the remaining budget. Essentially, the projects that represent low-hanging fruit and can be accomplished easily might warrant higher priority. Another factor that might influence priorities is the impact on the traveling public. Activities that require tunnel lane closures for an extended period may be given priority by grouping them with other activities within the same tunnel that can be accomplished during the same closure. Many factors go into an owner's ultimate priority decisions, but the MOE methodology presented in NCHRP Report 816 provides a first assessment to assist an owner in making these decisions.

The owner should review the NCHRP prioritized list and assign its own project priorities. Ultimately, it is the user's prioritization that will be used for the funding and staffing. NCHRP Report 816 provides complex examples for the selected preservation actions and new priorities assigned by the owner.

Implementation of Preservation Actions

The challenge of finding adequate funding to fulfill all agency needs has led agencies to accomplish the identified preservation actions over a period of time, in concert with their 5-, 6-, or 10-year capital plans. The capital plans may be developed based on an anticipated budget (top-down) or by planning preservation actions to be completed each year (bottom-up). Alternatively, some agencies may elect to implement preservation actions based on risk instead of a capital plan. If an agency has tunnel elements that are considered high risk, the agency may need to reprioritize its original capital plans by submitting updates at appropriate times in its business process. In addition, events may occur at the tunnel that would necessitate a re-prioritization of preservation actions to address the changed condition.

Section 3

Key Findings

Based on the literature reviewed, the following findings are noted to assist in addressing NTSB R-16-02:

- **Finding 1** – The transit industry should consider establishing a rating system, standard evaluation procedures, and a prioritization method for system components, including tunnels. A rating system and condition assessment procedures will provide numerical justification and prioritization for repairs or rehabilitation. A comprehensive prioritization method may consider the following items: effectiveness, a risk-based analysis, capital funding and staffing programs to accomplish tunnel preservation goals and serve as a training tool for new personnel. This finding fulfills National Safety Plan objectives to manage the safety risks and safety hazards within public transportation systems. The finding can also assist transit agencies that receive federal financial assistance [18,19] in implementing TAM for their capital assets used to provide public transportation.
- **Finding 2** – Based on the comparison of two condition assessment methods, NCHRP Report 816, the latest revision, can be adapted to develop condition assessments for rail transit tunnels. The NCHRP Report 816 provides a process for prioritizing needs, using an overall measure of effectiveness calculated using a risk-based urgency score, and developing capital funding and staffing programs to accomplish tunnel preservation goals. The procedures described in NCHRP Report 816 can be considered along with the SNTI,[20] which contains instructions for submitting the inventory and inspection data to the FHWA. The SNTI is dedicated to highway infrastructure; therefore, it needs to be adjusted for transit applications.
- **Finding 3** – Adapt tunnel inspection and repair methods to transit applications using various sources such as the FHWA "Technical Manual for Design and Construction of Road Tunnels – Civil Elements," AWSD1.1/D1.1 for structural steel repairs, AASHTO Specifications for repair of steel fastening systems, and sources identified in the FTA Report - *Rail Tunnel Design, Construction, Maintenance and Rehabilitation* (unpublished as of this report date). This would provide standards or recommended practices identifying, characterizing, and repairing typical defects in transit tunnel systems.

[18] FTA National Public Transportation Plan, 2017 edition, Washington, DC.
[19] FTA *TAM Facility Performance Measure Reporting Guidebook, op. cit.*
[20] FHWA-HIF-15-006, *op. cit.*

Appendix A

Detailed Example of Tunnel Prioritization Using NCHRP 816

This example is intended to illustrate the steps an agency would take to analyze and prioritize preservation actions for tunnel operations and maintenance. While the example is fictional, manipulated real-world data was used to illustrate the impact of many different preservation actions in tunnels with varied average daily traffic and conditions. This example is an extension of the example agency's (Agency X) tunnels and preservation actions presented in the core sections of this guide. More details from this example are presented in NCHRP Report 816 Appendix D.

Example Description

The agency has allocated $5 million for the following fiscal year for tunnel preservation. The supervisor has led several internal and external evaluations of the six tunnels in the system and has compiled a list of potential preservation actions. At this point, the tunnel supervisor has presented a list of 32 proposed actions resulting from consultant investigations and recommendations, internal observations, and customer complaints to the tunnel owner. This report presents only action items from Tunnel 6 (Average Daily Traffic [ADT] 75,000, high-traffic urban tunnel accessing a major city in proximity to a river).

Step 1. Establish agency (LOS and relevant importance of each. Across its entire transportation system, the agency has defined six LOS categories—Reliability, Safety, Security, Preservation, Quality of Service, and Environment. The weights for each LOS are presented in Table 5.

Table A-1 *LOS Weights for This Example*

	LOS	Weight (%)
1	Safety	40
2	Reliability	20
3	Preservation	18
4	Quality of service	15
5	Security	5
6	Environment	2

Step 2. Develop tunnel performance measures for each recommended category. Performance measures provide a means of evaluating how well the overall goal is being achieved by evaluating the performance in a specific area. Each year and as conditions warrant, the agency can decide if its current performance measures are effective and will continue to be tracked during subsequent years or if modification of performance measures is prudent. Table

A-2 presents tunnel performance measures for each recommended category and preservation action.

Table A-2 *Tunnel #s for Each Recommended Category*

LOS	Reliability	Safety	Security	Preservation	Quality of Service	Environment	LOS Score
Weights	***20%***	***40%***	***5%***	***18%***	***15%***	***2%***	
1	4	5	N/A	4	5	N/A	
2	4	4	N/A	5	N/A	N/A	
3	N/A	1	N/A	3	2	N/A	
4	N/A	3	N/A	5	3	N/A	
5	3	4	5	N/A	2	N/A	
6	4	3	1	4	2	N/A	
7	N/A	2	N/A	N/A	N/A	5	
8	4	5	N/A	3	2	N/A	

Step 3. Summarize tunnel needs based on condition inspection and regulatory requirements. Preservation actions that were selected by the tunnel supervisor:

1. Remove existing concrete tunnel ceiling.
2. Install flood gates.
3. Repair spalled concrete tunnel barriers.
4. Repair spalls on arch and walls.
5. Install new CCTV cameras and system.
6. Install overnight truck detection equipment and system, remove existing.
7. Install oil-water separator.
8. Rehabilitate and upgrade existing ventilation system.

Step 4. Develop LOS score for each tunnel – LOS standard. Ratings for each LOS category are multiplied by the corresponding weight, summed, and then divided by 5 to achieve a LOS score of between 0 and 100 for a preservation action.

Note that defined levels of service and their associated weights were determined by the AAMT in this example. N/A signifies that no rating was assigned to this LOS standard and is taken as a zero in the calculation.

1. LOS score = [4(20) + 5(40) + 0(5) + 4(18) + 5(15) + 0(2)]/5 = 427/5 = 85.4
2. LOS score = [4(20) + 4(40) + 0(5) + 5(18) + 0(15) + 0(2)]/5 = 330/5 = 66.0
3. LOS score = [0(20) + 1(40) + 0(5) + 3(18) + 2(15) + 0(2)]/5 = 124/5 = 24.8
4. LOS score = [0(20) + 3(40) + 0(5) + 5(18) + 3(15) + 0(2)]/5 = 255/5 = 51.0
5. LOS score = [3(20) + 4(40) + 5(5) + 0(18) + 2(15) + 0(2)]/5 = 275/5 = 55.0

6. LOS score = [4(20) + 3(40) + 1(5) + 4(18) + 2(15) + 0(2)]/5 = 307/5 = 61.4
7. LOS score = [0(20) + 2(40) + 0(5) + 0(18) + 0(15) + 5(2)]/5 = 90/5 = 18.0
8. LOS score = [4(20) + 5(40) + 0(5) + 3(18) + 2(15) + 5(2)]/5 = 364/5 = 72.8

The remaining preservation actions were rated based on their impact on the six established levels of service. All eight preservation actions, their ratings, and final calculated LOS scores are summarized in Table A-3.

Table A-3 *Example LOS Ratings and LOS Scores*

LOS	Reliability	Safety	Security	Preservation	Quality of Service	Environment	LOS Score
Weights	*20%*	*40%*	*5%*	*18%*	*15%*	*2%*	
Preservation Action							
1	4	5	N/A	4	5	N/A	85.4
2	4	4	N/A	5	N/A	N/A	66.0
3	N/A	1	N/A	3	2	N/A	24.8
4	N/A	3	N/A	5	3	N/A	51.0
5	3	4	5	N/A	2	N/A	55.0
6	4	3	1	4	2	N/A	61.4
7	N/A	2	N/A	N/A	N/A	5	18.0
8	4	5	N/A	3	2	N/A	72.8

Step 5. Develop Cost-Effectiveness (CE) score for each tunnel. Next, the cost-effectiveness of each preservation action must be considered. The tunnel supervisor has compiled the following information for each preservation action to calculate the CE score:

- Capital cost (initial cost of the preservation action in present-value dollars; includes labor and equipment)
- Agency oversight cost (generally taken as a percentage of the capital cost)
- Change in annual costs considering energy, maintenance, closures, reduction in accidents, reduction in staff, and so forth
- ADT for each tunnel
- Service life after improvement

The information listed above was prepared by the agency and is listed in Table A-4.

Table A-4 *Cost-Effectiveness Scores for All Preservation Actions – Part 1*

Preservation Action (PA)	Capital Cost ($)	Agency Oversight Cost ($)	Annual Change in Costs ($)	PV of LCC ($)	Remaining Life due to PA	ADT (x 1000)	ALCC ($)	Annual Cost per Daily Vehicle ($)	CE Score
1	8,000,000	800,000	–20,000		50	75			
2	8,000,000	320,000	0		100	75			
3	700,000	70,000	0		50	75			
4	1,000,000	100,000	0		50	75			
5	220,000	22,000	0		20	75			
6	170,000	17,000	0		20	75			
7	90,000	9,000	0		20	75			
8	3,700,000	370,000	0		20	75			

After compiling the above information for each preservation action, the PV (present value) of all future savings can be calculated. This must consider the discount rate, which is assumed to be 3%.

$$PV = \sum_{n=1}^{n} (\text{annual change in cost})/(1 + i)^n$$

Where i = 3% discount rate, n = remaining life due to PA.

Table A-5 presents annual savings of preservation action No. 1.

Table A-5 *PV of Annual Saving for Preservation Action #1*

Year	(1+i)n	Annual Saving	Year	(1+i)n	Annual Saving	Year	(1+i)n	Annual Saving
1	1.03	19,417	20	1.81	11,074	40	3.26	6,131
2	1.06	18,852	21	1.86	10,751	41	3.36	5,953
3	1.09	18,303	22	1.92	10,438	42	3.46	5,779
4	1.13	17,770	23	1.97	10,134	43	3.56	5,611
5	1.16	17,252	24	2.03	9,839	44	3.67	5,447
6	1.19	16,750	25	2.09	9,552	45	3.78	5,289
7	1.23	16,262	26	2.16	9,274	46	3.90	5,135
8	1.27	15,788	27	2.22	9,004	47	4.01	4,985
9	1.30	15,328	28	2.29	8,742	48	4.13	4,840
10	1.34	14,882	29	2.36	8,487	49	4.26	4,699
11	1.38	14,448	30	2.43	8,240	50	4.38	4,562
12	1.43	14,028	31	2.50	8,000			
13	1.47	13,619	32	2.58	7,767			
14	1.51	13,222	33	2.65	7,541			
15	1.56	12,837	34	2.73	7,321			

Table A-5 (cont'd) *PV of Annual Saving for Preservation Action #1*

Year	(1+i)n	Annual Saving	Year	(1+i)n	Annual Saving	Year	(1+i)n	Annual Saving
16	1.60	12,463	35	2.81	7,108			
17	1.65	12,100	36	2.90	6,901			
18	1.70	11,748	37	2.99	6,700			
19	1.75	11,406	38	3.07	6,505			
						Total saving		**514,595**

Table A-6 presents the present value of the life-cycle cost that is calculated as follow:

PV of LCC = (capital cost + agency oversight cost) – PV of annual saving

For preservation action No. 1:

$$PV = \sum_{n=1}^{50} (20{,}000)/(1 + 0.03)^n$$

Table A-6 *Cost-Effectiveness Scores for All Preservation Actions – Part 2 (PV of LCC)*

Preservation Action (PA)	Capital Cost ($)	Agency Oversight Cost ($)	Annual Change in Costs ($)	PV of LCC ($)	Remaining Life due to PA	ADT (x 1000)	ALCC ($)	Annual Cost per Daily Vehicle ($)	CE Score
1	8,000,000	800,000	–20,000	8,285,405	50	75			
2	8,000,000	320,000	0	8,320,000	100	75			
3	700,000	70,000	0	770,000	50	75			
4	1,000,000	100,000	0	1,100,000	50	75			
5	220,000	22,000	0	242,000	20	75			
6	170,000	17,000	0	187,000	20	75			
7	90,000	9,000	0	99,000	20	75			
8	3,700,000	370,000	0	4,070,000	20	75			

Annualized Life-Cycle Cost (ALCC)

$$ALCC = C * [i*(1+i)^n] / [(1+i)^n-1] – A$$

Where,

- C = capital cost + agency oversight cost, $
- i = 3%, discount rate %
- n = remaining life resulting from improvement, years, and
- A = annual change in cost (cost associated with energy, maintenance, closures, reduction in accidents, reduction of staff, etc.), $ (negative if savings)

For preservation action No. 1, ALCC = (8,000,000 + 800,000) * $[0.03*(1+0.03)^{50}]$ / $[(1+0.03)^{50}-1]$ – 20,000 = 322,016.

For preservation action No. 2, ALCC = (8,000,000 + 320,000) * $[0.03*(1+0.03)^{100}]$ / $[(1+0.03)^{100}-1]$ – 0 = 263,300.

For preservation action No. 3, ALCC = (700,000 + 70,000) * $[0.03*(1+0.03)^{50}]$ / $[(1+0.03)^{50}-1]$ – 0 = 29,926.

For preservation action No. 4, ALCC = (1,000,000 + 100,000) * $[0.03*(1+0.03)^{50}]$ / $[(1+0.03)^{50}-1]$ – 0 = 42,752.

For preservation action No. 5, ALCC = (220,000 + 22,000) * $[0.03*(1+0.03)^{20}]$ / $[(1+0.03)^{20}-1]$ – 0 = 16,266.

For preservation action No. 6, ALCC = (170,000 + 17,000) * $[0.03*(1+0.03)^{20}]$ / $[(1+0.03)^{20}-1]$ – 0 = 12,569.

For preservation action No. 7, ALCC = (90,000 + 9,000) * $[0.03*(1+0.03)^{20}]$ / $[(1+0.03)^{20}-1]$ – 0 = 6,654.

For preservation action No. 8, ALCC = (3,70,000 + 370,000) * $[0.03*(1+0.03)^{20}]$ / $[(1+0.03)^{20}-1]$ – 0 = 273,568.

The summary of annualized life-cycle cost is presented in Table A-7.

Table A-7 *Cost-Effectiveness Scores for All Preservation Actions – Part 3 (ALCC)*

Preservation Action (PA)	Capital Cost ($)	Agency Oversight Cost ($)	Annual Change in Costs ($)	PV of LCC ($)	Remaining Life due to PA	ADT (x 1000)	ALCC ($)	Annual Cost per Daily Vehicle ($)	CE Score
1	8,000,000	800,000	–20,000	8,285,405	50	75	322,016		
2	8,000,000	320,000	0	8,320,000	100	75	263,300		
3	700,000	70,000	0	770,000	50	75	29,926		
4	1,000,000	100,000	0	1,100,000	50	75	42,752		
5	220,000	22,000	0	242,000	20	75	16,266		
6	170,000	17,000	0	187,000	20	75	12,569		
7	90,000	9,000	0	99,000	20	75	6,654		
8	3,700,000	370,000	0	4,070,000	20	75	273,568		

Annual Cost per Average Daily Vehicle

$$ACDV = ALCC/ADT$$

Where:

ACDV = annual cost per average daily vehicle, $
ALCC = annual life-cycle cost (previously calculated), $
ADT = average daily traffic, number of vehicles

The annual cost per average daily vehicle is presented in Table A-8.

Table A-8 *Cost-Effectiveness Scores for All Preservation Actions – Part 4*

Preservation Action (PA)	Capital Cost ($)	Agency Oversight Cost ($)	Annual Change in Costs ($)	PV of LCC ($)	Remaining Life due to PA	ADT (x 1000)	ALCC ($) (Eq. 5-5)	Annual Cost per Daily Vehicle ($)	CE Score (Eq. 5-6)
1	8,000,000	800,000	–20,000	8,285,405	50	75	322,016	4.29	
2	8,000,000	320,000	0	8,320,000	100	75	263,300	3.51	
3	700,000	70,000	0	770,000	50	75	29,926	0.40	
4	1,000,000	100,000	0	1,100,000	50	75	42,752	0.57	
5	220,000	22,000	0	242,000	20	75	16,266	0.22	
6	170,000	17,000	0	187,000	20	75	12,569	0.17	
7	90,000	9,000	0	99,000	20	75	6,654	0.09	
8	3,700,000	370,000	0	4,070,000	20	75	273,568	3.65	

Cost-Effectiveness Score

Finally, a cost-effectiveness score can be determined based on the ACDV values calculated for each preservation action. For this set of data, a value of 10 is assigned as the multiplier in the denominator.

$$CE = 100/[(ALCC/ADT)*10],\ CE = 100 \text{ if } (100/[(ALCC/ADT)*10])>100$$

Where,

- CE = cost-effectiveness score
- ADT = average daily traffic, number of vehicles
- ALCC/ADT = annual life-cycle cost per daily vehicle.

The cost-effectiveness score for all eight preservation actions is presented in Table A-9.

Table A-9 *Cost-Effectiveness Scores for All Preservation Actions – Part 5 (CE Score)*

Preservation Action (PA)	Capital Cost ($)	Agency Oversight Cost ($)	Annual Change in Costs ($)	PV of LCC ($)	Remaining Life due to PA	ADT (x 1000)	ALCC ($) (Eq. 5-5)	Annual Cost per Daily Vehicle ($)	CE Score
1	8,000,000	800,000	–20,000	8,285,405	50	75	322,016	4.29	2.3
2	8,000,000	320,000	0	8,320,000	100	75	263,300	3.51	2.8
3	700,000	70,000	0	770,000	50	75	29,926	0.40	25.1
4	1,000,000	100,000	0	1,100,000	50	75	42,752	0.57	17.5
5	220,000	22,000	0	242,000	20	75	16,266	0.22	46.1
6	170,000	17,000	0	187,000	20	75	12,569	0.17	59.7
7	90,000	9,000	0	99,000	20	75	6,654	0.09	100.0
8	3,700,000	370,000	0	4,070,000	20	75	273,568	3.65	2.7

Step 6. Develop Risk-Based Urgency (RBU) score for each tunnel. The final component required to calculate the overall measure of effectiveness is the RBU score. The tunnel owner has compiled the following information for each preservation action:

- Remaining life of asset before the preservation action is implemented
  - If the preservation action is installing a new component that is not currently part of the tunnel system (i.e., manual fire alarm boxes in Tunnel No. 1), then the remaining life = 0.
- Original service life of asset
- Current condition of asset
  - Rate good (1), fair (2), poor (3), or severe (4).
  - Rate N/A whenever the proposed preservation action is installing a component that is new to the tunnel system.
- Is the preservation action related to a code or standard compliance issue?
- Enter yes (Y) or no (N).
- Risk of an unplanned event probability.
  - Rate 1 to 3, with 1 representing low probability and 3 representing high probability.

Once this information is entered into the metric, the user can assign an RBU rating of 1 to 10 considering all the information collected. See Table A-10 for a complete listing of the RBU score summary for all preservation actions.

Table A-10 *Example Risk-Based Urgency Scores*

Preservation Action (PA)	Remaining Life	Theoretical Service Life	% Life Expended	Condition 1 to 4	Regulatory Compliance Issue	Risk of Unplanned Event Probability (1 to 3)	RBU Rating (1 to 10)	RBU Score (RBU rating x 10)
1	0	50	100	3	N	1	10	100.0
2	N/A	100	N/A	N/A	N	3	6	60
3	2	50	96	2	N	1	2	20
4	5	50	90	2	N	1	2	20
5	N/A	N/A	N/A	N/A	N/A	1	5	50
6	0	20	100	4	N	3	8	80
7	N/A	N/A	N/A	N/A	Y	1	3	30
8	1	25	96	2	Y	3	8	80

Step 7. Determine weighted percentage for LOS score, CE score and RBU score. Now that all three scores (LOS, CE, and RBU) have been calculated, the overall measure of effectiveness can be determined. To allow for varying agency priorities and goals, weights must be assigned to each score and add up to 100 percent. The AAMT has assigned the following weights to each score:

- LOS score: 35%
- CE score: 20%
- RBU score: 45%
- Total = 100% OK

Step 8. Calculate overall Measure of Effectiveness (MOE) score for each tunnel. To calculate the overall MOE, each score is multiplied by the applicable weight and summed:

Total Score = LOS score * (35/100) + CE score * (20/100) + RBU score * (45/100)

Table A-11 shows the results of this calculation for the trench drain example. The resulting MOE scores will be used to prioritize the improvements.

1. Total Score = 85.4 * (35/100) + 2.3 * (20/100) + 100.0 * (45/100) = 75.4
2. Total Score = 66.0 * (35/100) + 2.8 * (20/100) + 60.0 * (45/100) = 50.7
3. Total Score = 24.8 * (35/100) + 25.1 * (20/100) + 20.0 * (45/100) = 22.7
4. Total Score = 51.0 * (35/100) + 17.5 * (20/100) + 20.0 * (45/100) = 30.4
5. Total Score = 55.0 * (35/100) + 46.1 * (20/100) + 50.0 * (45/100) = 51.0
6. Total Score = 61.4 * (35/100) + 59.7 * (20/100) + 80.0 * (45/100) = 69.4
7. Total Score = 18.0 * (35/100) + 100.0 * (20/100) + 30.0 * (45/100) = 39.8
8. Total Score = 72.8 * (35/100) + 2.7 * (20/100) + 80.0 * (45/100) = 62.0

Table A-11 *Example MOE Scores*

Levels of Service	LOS Score	CE Score	RBU Score	MOE Score
Weights	*35%*	*20%*	*45%*	
Preservation Action				
1	85.4	2.3	100.0	75.4
2	66.0	2.8	60	50.7
3	24.8	25.1	20	22.7
4	51.0	17.5	20	30.4
5	55.0	46.1	50	51.0
6	61.4	59.7	80	69.4
7	18.0	100.0	30	39.8
8	72.8	2.7	80	62.0

Step 9. Implement prioritized tunnel preservation action in updated capital plans. Now that all the preservation actions have been assigned a calculated priority based on total score, they can be sorted from highest to lowest priority. The user can override this prioritization by entering a user-designated priority. The user priority enables users to consider operational, political, or other factors that affect their planning for project implementation. The user has entered their rankings into the "User-Defined Priority" column in Table D-11.

Priorities were established with consideration of improving safety; actions that improved safety were ranked higher than those that did not impact safety. Table D-11 shows the complete example of the user-defined prioritization of preservation actions.

Step 10. Evaluate performance. Further analysis is needed to evaluate the preservation actions that can be accomplished within the funding limit, identify funding needs for future years, or evaluate the staffing needs for future years. To facilitate these analyses, the user should collect the following information:

- Percent of capital cost attributed to labor
- Year that preservation action will be funded (this term is most effectively determined through trial and error by adjusting the user-priority values).

For more details on this example, refer to NCHRP Report 816.

U.S. Department of Transportation
Federal Transit Administration

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