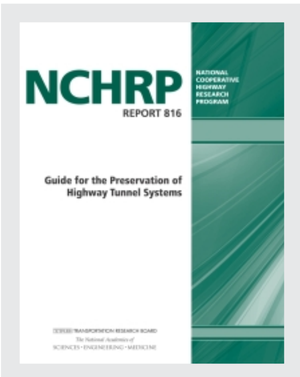

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 816

Guide for the Preservation of Highway Tunnel Systems

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TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments and by committees of AASHTO. Topics of the highest merit are selected by the AASHTO Standing Committee on Research (SCOR), and each year SCOR's recommendations are proposed to the AASHTO Board of Directors and the Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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Learn more about the Transportation Research Board at **www.TRB.org**.

COOPERATIVE RESEARCH PROGRAMS

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FOREWORD

By Waseem Dekelbab
Staff Officer
Transportation Research Board

This report presents a guide for the preservation of highway tunnel systems to (1) assist tunnel owners in making informed decisions using an asset management process to support their prioritization of highway tunnel preservation actions and (2) provide executives with credible, evidence-based information on capital funding needs for tunnel improvements as part of their overall transportation system funding, as well as a means for communicating those needs. This guide provides a process for prioritizing needs, using an overall measure of effectiveness that is calculated using a risk-based urgency score, and developing capital funding and staffing programs to accomplish tunnel preservation goals, and also serves as a training tool for new personnel. The material in this report will be of immediate interest to tunnel owners and operators.

Tunnels are defined as enclosed roadways with vehicle access that is restricted to portals, regardless of type of structure or method of construction. Tunnels do not include highway bridges, railroad bridges, or other bridges over a roadway. Tunnels are structures that require special design considerations that may include lighting, ventilation, fire protection systems, and emergency egress capacity based on the owner's determination. Tunnel preservation includes actions or strategies that prevent, delay, or reduce deterioration of tunnel systems (preventive maintenance); restore the function of existing tunnels (repair or rehabilitation); and keep tunnels in good condition and extend their useful life. Every year, significant public funds are needed to inspect and maintain tunnels that were not designed to be easily inspected and maintained. Nevertheless, well-planned preventive maintenance is a cost-effective strategy to keep tunnels safe and operational.

Practitioners often apply preservation strategies on the basis of judgment or common sense using available resources. However, it is difficult to translate these strategies into coherent and convincing arguments that will lead to support for aggressive and well-planned programs of highway tunnel preservation. Also, tunnels are complex structures that include mechanical, electrical, life safety, and structural systems. Deciding the priorities among these disparate elements can be very difficult. Therefore, tunnel programs may be inadequately funded due to absence of a credible, quantitative basis for measuring effectiveness.

Research was performed under NCHRP Project 14-27 by Gannett Fleming, Inc., to develop a guide for possible adoption by AASHTO that will (1) assemble a catalog of highway tunnel preservation actions, (2) quantify the benefits of tunnel preservation actions, (3) provide decision-making tools to optimize tunnel preservation actions, and (4) develop a method to determine appropriate levels of funding and staffing to achieve agency-selected goals and performance measures.

The research agency's final report that documents the entire research effort is available on the NCHRP 14-27 project description page on the TRB website.

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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

CHAPTER 1

Introduction to the Guide

1.1 Why Tunnel Preservation?

1.1.1 Background

Highway tunnels play an important role in our nation's transportation network, providing access through difficult terrain, below waterways, and under other structures. Highway tunnels are often critical links within a region's transportation system; without them, the remaining roadways would be overburdened, travel would take longer, and routes would be less direct. Maintaining these assets in a state of good repair is paramount to maintaining the viability of the overall transportation network. This maintenance, which includes preservation, must be planned and, more importantly, budgeted for by tunnel owners.

As with the nation's other infrastructure funding, funding for highway tunnel preservation and improvements is limited; multiple agencies and, frequently, multiple departments within an agency, compete for available funding. Overall, available funding is inadequate to maintain the infrastructure. Identifying the specific improvements and preservation needed and planning for these as future expenditures is critical. Once the needs are identified, they must be prioritized. Tunnels are only one part of a transportation agency's overall asset inventory, which also includes, for example, roadway pavements, bridges, culverts, signs, and light poles. Tunnel needs have to be weighed against the other asset preservation needs and prioritized based on the entire agency's goals and objectives.

It is common knowledge that many tunnels in the United States are decades old. Approximately 225 highway tunnels in the United States over 300 feet in length are more than 50 years old, and 128 highway tunnels are over 70 years old, as shown in Table 1-1.[1,2] Maintenance of these older facilities can be significant, and major rehabilitation work is often needed. Tunnels more than 25 years old were most likely not designed to current fire and life safety standards, so significant upgrades to their ventilation and electrical systems are needed.

Another problem becoming more prevalent is that as existing tunnels age, so does the staff that maintains them. It has been estimated that about 50% of tunnel owners' personnel will be eligible to retire in the next 10 years.[3] As this occurs, agencies will lose a wealth of historical information, sometimes dating back to the original tunnel construction, including the specific problems that were experienced and the maintenance that was performed through the years.

1.1.2 What Is Tunnel Preservation?

Similar to the AASHTO-adopted definition of bridge preservation,[4] 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

Table 1-1. Summary of highway tunnel ages.

Tunnel Age	Year Constructed	Number of Tunnels*
1 to 10 years	2003 to present	6
11 to 20 years	1992 to 2002	17
21 to 30 years	1982 to 1992	36
31 to 40 years	1972 to 1982	21
41 to 50 years	1962 to 1972	57
51 to 60 years	1952 to 1962	56
61 to 70 years	1942 to 1952	41
71 to 80 years	1932 to 1942	64
81 to 90 years	1922 to 1932	34
91 to 100 years	1912 to 1922	6
101 to 110 years	1902 to 1912	7
111 to 120 years	1892 to 1902	10
121 to 130 years	1882 to 1892	6
More than 131 years	1881 and prior	1

*The FHWA in 2003 requested that the highway inventory be limited to tunnels exceeding 300 feet in length. Whereas agencies typically followed this definition, a few tunnels are included in this inventory that are less than 300 feet in length.

condition; and extend their lives. Tunnel preservation may also include preventive maintenance, cyclical preventive maintenance (activities on a predetermined interval), condition-based preventive maintenance, and rehabilitation.

Further discussion of definitions for the various types of preservation actions (PAs) for tunnels is presented in Chapter 4.

1.2 Purpose of the Guide

Due to funding limitations and an aging infrastructure, tunnel owners are focusing on preserving their assets to extend their useful service life. This report, *NCHRP Report 816: Guide for the Preservation of Highway Tunnel Systems*, provides a tool to assist tunnel owners in making informed decisions, using an asset management process to support their prioritization of highway tunnel preservation actions. Beginning with identifying preservation actions, the guide provides a process for prioritizing needs and developing capital funding and staffing programs to accomplish tunnel preservation goals. Thus, the process outlined in the guide will aid executives in supporting capital funding needs for tunnel improvements as part of their overall transportation system funding, and will help in communicating those needs.

As agency staff members who maintain these assets retire, their knowledge and experience need to be transferred to the next generation. There is great need for tunnel preservation documentation of preservation actions and the rationale for when such actions are to be implemented. This guide provides this methodology and also serves as a training tool for new personnel.

1.3 Using an Asset Management Approach for Highway Tunnel Preservation

The 2011 *AASHTO Transportation Asset Management Guide: A Focus on Implementation* provides an effective framework for transportation officials to understand and use in setting up an asset management approach for maintaining and preserving their overall transportation network. The 2011 guide recommends that a comprehensive asset management plan do the following:

- Take a network view: A holistic view that considers the entire transportation network as a whole is dependent upon its parts, and, in order to perform, each part needs other parts to function effectively. For example, in an overall highway system that includes tunnels, the performance of both highways and tunnels must be considered for the overall system to function as intended.
- Align with strategic directions: The transportation agency's highest officials must be committed to using a transportation asset management process as part of the organization's strategic direction in order to achieve policy goals and objectives.
- Provide leadership that aligns the agency: Leadership from all parts of the agency (e.g., senior management, planning, operations, and maintenance) should be involved in the asset management process so that all aspects are considered for making cost-effective decisions that align with the strategic direction.
- Communicate with stakeholders: The agency's use of performance measures to document accomplishments against agency goals and objectives, commonly defined as level-of-service (LOS) standards, is critical for the organization to function with transparency and accountability, as well as for documenting conditions for obtaining funding streams to improve the agency's assets.
- Make data-driven, informed decisions: An asset management approach requires an agency to have good, historical, readily accessible data on their transportation assets, including their condition, performance, and other characteristics related to the life of the asset and its ability to continue to provide reliable, safe service. Tunnel owners using the approach recommended in this guide will have sufficient knowledge of their tunnel systems from inspections, day-to-day operations, and routine and periodic maintenance activities, such that preservation actions can be readily identified and prioritized.
- Integrate agency programs and budgets: The agency must align strategies, plans, programs, and budgets to ensure that the agreed LOSs are delivered to current and future customers in the most cost-effective manner. Using the tools recommended in this guide will be an important step in helping to develop and prioritize capital budgets for accomplishing the preservation actions.
- Monitor outcomes: It is absolutely necessary that an agency monitor its performance against stated LOS standards to understand if the outcomes are being reached.
- Focus on continued improvement: Continued improvement should become part of any transportation agency's management approach and culture. Inherent in this continued improvement is conducting self-assessments and gap analyses on a regular basis.[5]

These concepts are applicable to an asset management approach for highway tunnel preservation as a subset of the transportation system. Chapters in this guide follow general concepts/themes outlined in the 2011 *AASHTO Transportation Asset Management Guide* through a systematic process identified in Figure 1-1. This flowchart presents an overview of the tunnel preservation asset management process further defined in this guide. The process identifies the following steps to be taken:

- The transportation agency assigns committee representatives knowledgeable of its overall transportation system to be members of the agency's asset management team (AAMT). The AAMT should be a multi-disciplined team with the expertise necessary for evaluating tunnel preservation actions, including structural, electrical, mechanical, lighting, civil, and geotechnical disciplines.
- The AAMT is responsible for defining the overall LOSs (goals) that the agency desires to achieve for its overall transportation system, of which highways, bridges, tunnels, culverts, lights, signs, and so forth are elements.
- The AAMT establishes the **relative importance of each LOS** within its agency. Establishment of the agency's LOS is a key component of its transportation asset management plan, and the

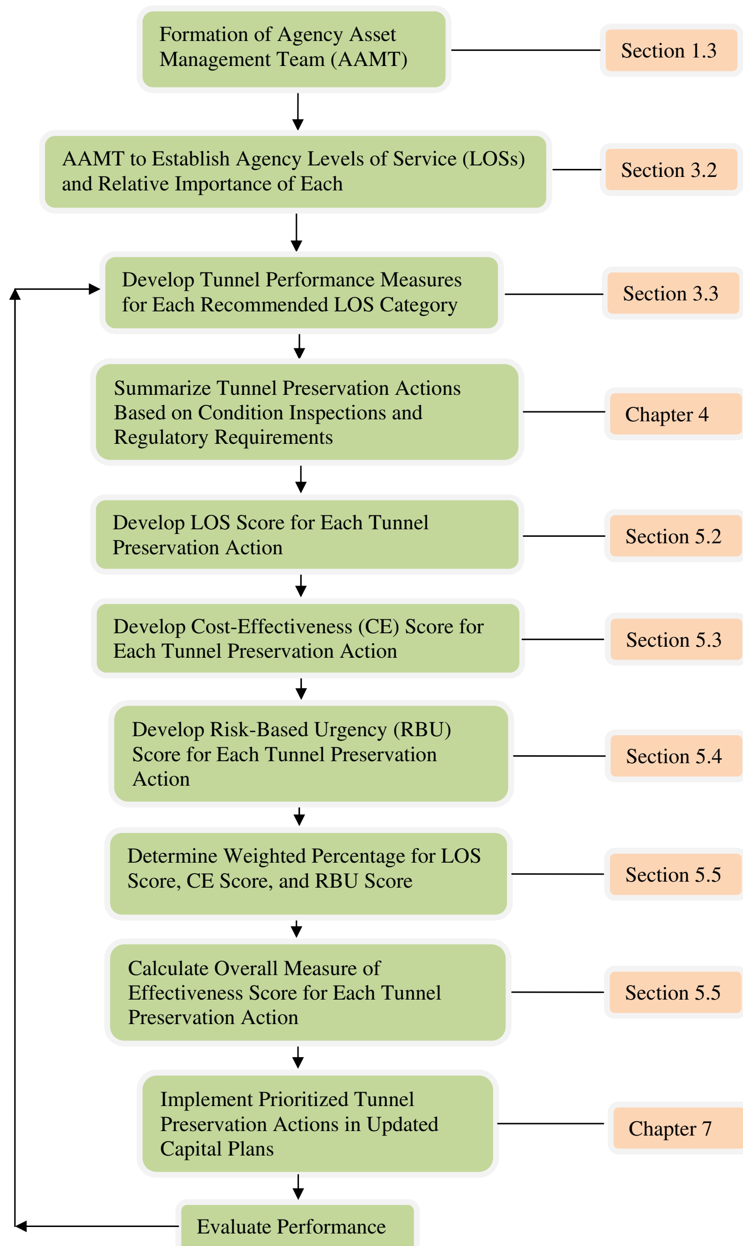


Figure 1-1. Highway tunnel preservation asset management flowchart.

identification of LOS priorities with respect to tunnels is a requirement for the tunnel preservation prioritization.

- The agency establishes specific **performance measures** for its transportation system elements based on each LOS to monitor progress in meeting each LOS.
- **Preservation actions** are identified for each tunnel through inspections and testing.
- For each preservation action, an **LOS score,** based on its significance in achieving the LOS, is developed.
- To compare alternatives based on **cost-effectiveness** (CE), life-cycle costs are calculated for each preservation action. Costs for each preservation action should include additional maintenance that could be incurred due to delaying of 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. The average daily traffic (ADT) is another parameter used in determining the cost-effectiveness of a preservation action.

- The urgency of the preservation action is evaluated using a **risk-based urgency (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.
- The combination of three scores (LOS, CE, and RBU) provides the overall **measure of effectiveness (MOE) score** for each preservation action and ultimately provides the basis of the prioritization.
- The tunnel owner reviews the prioritization and modifies it 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 on the specific needs for the preservation actions to be implemented in a given year. Staffing needed to implement the preservation actions may be procured through external contracts or through the hiring of new agency personnel.

1.4 Overview of the Guide

The elements included in each chapter of this guide are summarized in the following.

Chapter 1: Introduction to the Guide

- Provides the reasons tunnel preservation is needed.
- Provides a definition of tunnel preservation.
- Describes the purpose of the guide in assisting tunnel owners in implementing preservation actions through the use of an asset management approach.
- Summarizes the asset management approach, including a flowchart showing the various steps of the approach.
- Outlines each chapter's contents.

Chapter 2: Description of Tunnel Assets

- Describes the various complex tunnel systems that are interrelated.
- References Appendix A, which includes detailed information on these systems from the 2005 FHWA *Highway and Rail Transit Tunnel Inspection Manual*[6] and the 2015 FHWA *Tunnel Operations, Maintenance, Inspection, and Evaluation Manual* (TOMIE Manual)[7] to provide additional details of these systems.
- Reviews current tunnel design standards that address recent life safety standards. As rehabilitation or replacement of systems occurs to preserve older tunnels, many owners are looking to upgrade tunnel systems to improve safety through compliance with the National Fire Protection Association (NFPA) 502 standard.[8]
- References Chapter 4, Section 4.3, for examples of types of previously employed preservation actions to upgrade these systems to meet life safety standards.

Chapter 3: Establishing the Asset Management Framework

- Provides a background on the use of asset management systems for highway agencies.
- Recognizes that although tunnels are a subset of an agency's total transportation system, they provide an important link for the system to remain operational. Most transportation agencies

have overall goals and objectives, also known as LOSs, defined for maintaining and improving their transportation assets. In the absence of established LOSs, the transportation agency must establish them for its overall transportation network, of which tunnels are a part. The agency may deem it necessary to develop specific LOSs for its tunnels as a subset of its overall LOSs for the entire transportation system.
- Presents a discussion to aid the AAMT in selecting LOSs relative to the overall agency's goals and objectives.
- Provides examples of typical performance measures an agency might consider.

Chapter 4: Highway Tunnel Preservation Actions

- Defines AASHTO's tunnel preservation definitions for different types of maintenance (preventive, cyclical preventive, and condition-based preventive), rehabilitation, and replacement actions.
- Describes how preservation actions are established by using reliability-based inspection intervals from various sources (operational/management staff, staff/consultant inspections, testing agencies).
- Provides examples of preservation actions that an owner should consider after receiving results from a recent inspection.
- Provides a description of a particular agency's tunnels, showing both urban and rural tunnels and the associated ADT for each tunnel.
- References a catalog of typical preservation actions included in Appendix B to provide guidance as to the types of actions that are generally required for various tunnel systems.

Chapter 5: Measuring Effectiveness of Preservation Actions

- Provides a simple metric that can be used to prioritize preservation actions within a tunnel or across multiple tunnels.
- The metric uses three scores: the LOS score, the CE score, and the RBU score. Each score's calculation is discussed. A weighted combination of these scores results in the overall MOE, which is used to establish priorities.
- Additional guidance is provided for incorporating life-cycle cost analysis, present-value costs, and remaining life to evaluate preservation actions.
- The LOS score is used by tunnel owners to rate preservation actions to better achieve their overall LOS goals. Owners are knowledgeable about their overall transportation systems and will be expected to set the relative importance of each LOS in the development of the LOS score, reflecting the preservation actions that best accomplish the goals for their overall systems.
- Cost-effectiveness is evaluated considering capital cost, life-cycle costs, and the number of users.
- The RBU score for a preservation action considers remaining life, condition, regulatory requirements, and the risks of unplanned events such as earthquakes, floods, and fires.
- An example is provided to explain the use of the metric to calculate the overall MOE of each preservation action.

Chapter 6: Prioritization of Preservation Actions

- Using the MOE calculated in Chapter 5, an agency's tunnel preservation actions can be prioritized, regardless of whether the tunnel is in an urban or rural area or whether the improvements are for different tunnels or different systems within tunnels. The example developed in Chapter 5 is continued to show the calculated priority.

- Each agency has its own unique set of circumstances—budget limitations, the ability to close the tunnel to perform the work, and so forth—that affect the final prioritization. For this reason, the tunnel owner has the ability to adjust the final prioritization to suit agency needs.
- In addition to prioritizing preservation actions for its tunnel systems, an agency may also want to evaluate multiple alternatives for one preservation action. Two examples are provided to show how the metric could be used in this way.

Chapter 7: Implementation of Preservation Actions

- Describes typical funding sources based on research conducted with tunnel owners as part of this research project.
- Presents funding scenarios using both a top-down and a bottom-up approach, as illustrated by the example initiated in Chapter 5.
- Using the prioritized list of tunnel preservation actions and the funding year each will occur in, it is possible to develop the staffing needs for the agency for each year. An example is provided.
- Presents an example of how various costs (capital, labor, agency oversight, and materials) for each preservation action can be aggregated to support agency funding allocated for particular funding years.
- Describes how the metric supports an agency's ability to communicate tunnel preservation needs to decision makers so that funding streams over a realistic period will be sufficient to keep the tunnel systems in good operating condition.

Appendices

- Appendix A: Description of Tunnel Types and Systems
- Appendix B: Catalog of Preservation Actions
- Appendix C: Highway Tunnel Preservation Prioritization Flowchart
- Appendix D: Detailed Example

CHAPTER 2

Description of Tunnel Assets

2.1 Tunnel Systems

The AASHTO Technical Committee for Tunnels (T-20) defines tunnels as "enclosed roadways with vehicle access that is restricted to portals regardless of type of structure or method of construction."[(9)] They further define road tunnels "not to include enclosed roadways created by highway bridges, railroad bridges, or other bridges."[(9)]

Highway tunnels are complex facilities containing multiple systems that contribute to their overall functionality and the safety of the traveling public in the event of fires and accidents. Each of these multiple systems also includes many subsystems. FHWA's 2015 *Specifications for National Tunnel Inventory* categorizes these systems as shown in the following:

- Structural systems: These systems make up the primary structure of the tunnel or support its equipment and include the walls, roof, ceiling slabs, roof beams, portals, invert slabs, slabs on-grade, cross-passageways, equipment supports, joints, and gaskets.
- Civil systems: These systems consist of the wearing surface, traffic barriers, and pedestrian railings.
- Mechanical systems: These systems consist of the ventilation system, drainage system, emergency generator system, and flood gates. The ventilation and drainage systems contain fans, fan motors, pumps, pump motors, pump controllers, piping, and drains. The emergency generator system includes a generator, fuel storage tank, fuel day tanks, exhaust air louvers, damper actuator, generator control equipment, and conduits.
- Electrical systems: These systems include the tunnel's electrical distribution and emergency distribution systems. The electrical distribution system includes switchgear, motor control centers, starters, transformers, transfer switches, panel boards, conduits, raceways, and electrical outlets/receptacles. The emergency distribution system consists of uninterruptable power supply, batteries, and battery charging equipment.
- Lighting systems: These systems include the tunnel and emergency lighting systems. Both of these systems consist of light fixtures, fixture supports, bulb housings, lenses, light switches, junction boxes, wiring, conduit, cable, sensors, and controllers.
- Fire/life safety/security systems: These systems consist of fire detection, fire protection, emergency communication, and operations and security systems. Fire detection systems consist of control panels, initiating devices (heat and smoke detectors, pull-stations, etc.), notification appliances (strobes, horns, etc.), wiring, conduit, and cable. Emergency communication systems include communication devices [intercom, public address, emergency override frequency modulation (FM) radio rebroadcast, private emergency radios, cell phones, receivers, wiring, exchange devices, signs, controllers, speakers, and audio input equipment]. Tunnel operations and security systems include communication equipment [closed-circuit television (CCTV) cameras, telephones, radios, etc.].

- Signs: Signs include traffic signs, over-height detection systems, pedestrian signs, variable message boards, lane signals, fixture control cabinets, and conduits.
- Protective systems: These systems include steel corrosion, concrete corrosion, and fire protective coating systems.(10)

See Appendix A for detailed information on many of these systems taken from the 2005 FHWA *Highway and Rail Transit Tunnel Inspection Manual* and the 2015 FHWA TOMIE Manual.

2.2 Life Safety Systems

The NFPA 502 standard became a standard for life safety design of tunnels in 1981 but has since undergone significant revisions. Although NFPA 5000 has not been adopted as the governing code in most states, NFPA 502 has been, and continues to be, the standard for life safety design in new highway tunnels. As system rehabilitation or replacement occurs to preserve older existing tunnels, many owners are looking to upgrade tunnel systems to implement life safety system recommendations from NFPA 502. Although older tunnels are grandfathered in and not required to be retrofitted to meet the NFPA standard, many owners are considering preservation actions for operational and safety upgrades by complying with this standard to the degree possible.

The major systems and tunnel elements addressed in NFPA 502 include:

- Fire protection systems,
- Fire detection systems,
- Life safety systems,
- Emergency ventilation,
- Communication systems,
- Traffic control systems, and
- Electrical systems.(8)

See Chapter 4, Section 4.3, for examples of the types of preservation actions to upgrade these systems to meet life safety standards.

CHAPTER 3

Establishing the Asset Management Framework

3.1 Background

Transportation systems are most efficient when asset management principles are applied. Transportation systems can be safer, operate more cost-effectively, be maintained in good condition, be more environmentally friendly, and so forth, if an asset management framework is established. Asset management involves a systematic approach that includes transparent agency management and accountability, data-driven and repeatable decision-making processes, strategic risk mitigation strategies, and use of efficient financial methodologies (e.g., life-cycle costs, costs of delaying action).

Elements of asset management were first implemented by FHWA for bridges with the establishment of the National Bridge Inspection Standards in 1971,[11] which required regular inspection and documentation of inspections for all public bridges. In the early 1990s, bridge management software was provided by FHWA to assist state highway agencies in managing their bridge programs. This software provided a means to evaluate the condition and remaining life of the bridges to support decision making as part of an agency's overall bridge management program. Pavement management systems followed a similar track, with systems being implemented by some states in the early 1980s in an effort to better manage the pavement on their highway systems. An asset management approach is also being used for assets such as signs and culverts, but there is still a need for an overall asset management framework within some highway agencies.

The Moving Ahead for Progress in the 21st Century Act (MAP-21), which was signed into law in July 2012, required each state to develop a risk-based asset management plan with the goal of improving or preserving its assets and the performance of the overall system. One element of this risk-based asset management plan is the establishment of agency goals and objectives.

3.2 Establishing Goals and Objectives

Goals and objectives (commonly referred to as LOSs) addressing the overall transportation system need to be identified. Each transportation agency should establish an AAMT to define the various LOS standards or goals for the agency's overall transportation system. This AAMT should be a multi-disciplinary team with the expertise necessary for evaluating tunnel preservation actions, including structural, electrical, mechanical, lighting, civil, and geotechnical disciplines. 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 can tailor the goals to its tunnels.

3.2.1 Identifying Levels of Service for Tunnel Preservation

As transportation agencies implement asset management at the agency level and within each separate department, they must first establish their overall goals and objectives (LOSs) for their transportation network. These goals may vary over the course of many years depending on the facilities owned and their condition as part of their overall network, and may be revisited annually, biennially, or when changes dictate. The LOSs are high-level goals and encompass many different aspects of operations, including the reliability of the service provided by the tunnel, the safety to the traveling public and employees, the security of the asset, and the quality of service to the customer. For those agencies that own tunnels, a separate set of goals specific to tunnels may be considered if these goals differ greatly from the agency's overall transportation network LOSs.

Agencies worldwide have used a varied number of LOS standards to define the overall objectives that best fit their particular agency. The research for this guide revealed that agencies generally use the six LOSs described in the following as representative for establishing performance measures for tracking progress toward goal accomplishment. However, these do not preclude the agency from adding an LOS for unique situations or from modifying these representative LOS standards to best meet their objectives.

- 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?
- 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?
- 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?
- 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?
- 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 concrete/shotcrete surfaces), and environment (no leaks from groundwater penetration)?
- 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?

3.3 Monitoring Performance

An important element of the asset management process is monitoring agency performance concerning how well the overall goals and objectives are being achieved. Tunnel preservation actions are intended to improve the overall performance of the specific system, the overall tunnel, and the overall highway network. Improvements in performance resulting from preservation actions should be measurable through the use of performance measures.

Because the LOSs are broad categories and can be affected through a variety of actions (e.g., operational, organizational, physical changes), further refinement within each goal area is needed. Performance measures provide a means of evaluating how well the overall goal is being achieved by evaluating the performance in the specific area. The need for agencies to establish performance measures was mandated by MAP-21. MAP-21 required transportation agencies to develop performance targets and to track their performance in meeting those targets. Agencies owning tunnels must consider these assets when establishing their performance measures. 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. This process of establishing the targets, collecting data, monitoring, reviewing, and implementing changes is fundamental to a successful asset management approach for preservation of the agency's highway tunnels.

3.3.1 Performance Measures

Performance measures are used to monitor the agency's performance in meeting its prescribed LOS standards. When establishing the agency's performance measures and targets for each, the tunnels and associated systems should be considered. Performance measures provide a snapshot in time, reflecting the current performance of the tunnel assets. For example, tunnel fans, lighting, carbon monoxide (CO) detection systems, and CCTVs are all assets within a tunnel. Time between failures might be a performance measure that would reflect the performance of these systems. Time between failures after improvements are made, compared to what it was prior to the improvements, can be used to capture the change in performance with respect to the LOS standard.

Performance measures should be specific and measurable. Several other characteristics should be considered when developing performance measures for tunnels. The acronym SMARTER is commonly used to capture the attributes of performance measures:

- Specific: Provides sufficient clarity as to what is being measured.
- Measurable: Ensures that the performance measure can be quantified.
- Achievable: Sets realistic expectations as to what is required and what can be accomplished.
- Relevant: Relates to the organization's objectives and goals.
- Time-bound: Reflects the time frame over which action is required.
- Evaluation: Continues assessment of the appropriateness of the measures and target.
- Reassess: Reviews performance measures and targets on a regular basis.[12]

Examples of performance measures that apply to highway tunnels and allow a means to monitor the achievement of each goal area are provided in Table 3-1. Those in bold are suggested measures for consideration.

Table 3-1. Examples of performance measures.

Levels of Service	Performance Measures
Reliability	**1. Unscheduled tunnel closures (hours per year)** **2. Number of scheduled closures per year** **3. No more than Y closures of more than Z minutes per year (urban)** 4. Impact of work on transportation systems (i.e., lane closure causes X accidents on surrounding roadways per year) 5. Bidirectional traffic volume in one tunnel per year 6. Hours of tunnel closure per year due to unplanned maintenance operations
Safety	**1. Number of incidents/accidents per year** **2. Number of injuries or fatalities per year** **3. Water infiltration: number of closures to remove icicle formations on ceiling underside per year** 4. Number of fires per year 5. Structural condition rating of tunnel liner 6. Structural condition rating of suspended ceilings and other appurtenances (signs, lights)

Table 3-1. (Continued).

Levels of Service	Performance Measures
	7. General ventilation: percentage of time CO concentration is below target threshold at all sampling points 8. CO monitoring system: percentage of time system is calibrated/operational 9. Emergency ventilation–smoke control: percentage of time all fans are fully functional 10. Tunnel lights: percentage of lights available 11. Tunnel lane signals: percentage of lane signals available 12. Number of power outages per year 13. Water-based firefighting systems (including deluge systems): percentage of time system is fully functional 14. Standpipe system: percentage of time system is fully functional 15. Portable fire extinguishers: percentage available with current inspection 16. Fire pumps: percentage of time pumps are fully functional 17. Fire detection: percentage of time system is fully functional 18. Tunnel drainage: percentage of roadway drainage that is effective 19. Hydrocarbon detector: percentage of time system is fully functional
Security	**1. Percentage of time security cameras are functioning** **2. Percentage of time over-height detection systems are functioning** **3. Frequency of vehicles carrying hazardous materials through the tunnel** 4. Response time at time of event 5. Availability of emergency personnel 6. Number of incidents per year 7. Emergency response plan: • Complete and on file • Regular training exercise/drills/critiques conducted with all participating agencies • Records maintained for fire emergencies and drills, including a lessons-learned review of each incident with participating agencies 8. Number of enforcement events or citations
Preservation	**1. Severity of water leakage per length of tunnel** **2. Vibration of fan and pump bearings** **3. Oil quality** **4. Regular maintenance of emergency power generation** 5. Concrete integrity: meets minimum condition rating of X (to be established by the tunnel owner) 6. Water quality of hydronic systems 7. Oil testing of oil-insulated transformers 8. Infrared testing of electrical equipment 9. Regular maintenance of support space for heating, ventilation, and air-conditioning (HVAC) systems
Quality of Service	**1. Number of customer complaints** **2. Cleanliness** **3. Delay: average peak hour traffic delay** **4. Change in ADT** 5. Pavement International Roughness Index (IRI) 6. Number of tunnel closures or number of lane closures per year 7. Vertical and horizontal clearances, no obstructions 8. No missing tiles or less than X square feet of missing tiles 9. No dislodged ceiling panels 10. Signage, message signs easily readable
Environment	**1. No damage to environment (spills)** 2. Oil–water separator functioning as designed

CHAPTER 4

Highway Tunnel Preservation Actions

4.1 Definitions of Preservation Actions

Drawing on the definitions of preservation actions for bridges in the 2011 FHWA *Bridge Preservation Guide*,[4] the following definitions of preservation actions for tunnels are provided. Preservation actions include both preventive maintenance and rehabilitation activities.

4.1.1 Preventive Maintenance

Preventive maintenance is a planned strategy of cost-effective treatments to an existing tunnel and its systems that preserves the systems, retards future deterioration, and maintains or improves the functional condition of the systems (without substantially increasing structural capacity). Preventive maintenance includes cyclical (non-condition-based) and condition-based activities.

- Cyclical (non-condition-based) preventive maintenance: Activities performed at a predetermined interval and aimed to preserve existing tunnel element or component conditions. Tunnel element or component conditions are not always directly improved as a result of these activities, but deterioration is expected to be delayed. Such maintenance is typically based on manufacturer recommendations, research recommendations, or a maintenance intervention strategy (e.g., light bulb replacement, vibration testing of fan motors, exercising of emergency generators).
- Condition-based preventive maintenance: Activities that are performed on bridge elements as needed and identified through the tunnel inspection process. These activities are typically performed on a tunnel that is in overall good to fair condition to restore tunnel elements to a state of good repair. Similar to cyclical preventive maintenance activities, condition-based preventive maintenance activities are designed to extend the useful life of tunnels. These may include emergency or other unscheduled, time-sensitive maintenance or observed repair activities.

4.1.2 Rehabilitation

Rehabilitation involves major work required to restore the structural integrity of a tunnel or its systems, as well as work necessary to correct major safety defects. Rehabilitation could include structural repairs for capacity, operations, or safety improvements, as well as the addition of new tunnel systems as part of a fire and life safety assessment.

4.2 Establishing Preservation Actions

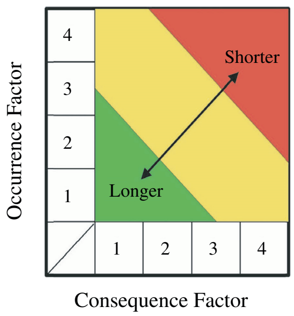
Asset management of tunnels involves a continuous cycle of assessment, maintenance, and preservation over the life of the asset. Knowing what is needed in terms of preservation actions comes through assessment of the tunnel and its systems, which begins with regular inspections.

With the promulgation of the anticipated National Tunnel Inspection Standards (NTIS), tunnels must be inspected every 2 years unless a risk assessment allows for this period to be extended. It is anticipated that many tunnel owners will use a reliability-based approach for tunnels, similar to that proposed for bridge inspection, per requirements of the NTIS.

The reliability-based approach that was developed for bridge inspection[13] is equally applicable to tunnels and provides a process for evaluating tunnel inspection scope and frequencies. The process involves three simple steps that evaluate inspections in terms of the likelihood and extent of damage that could occur within a tunnel:

- Step 1: Determine what can go wrong and how likely it is to occur. This step considers the likelihood of serious damage occurring and categorizes it within four *occurrence factors* ranging from remote (very unlikely) with a score of 1 to high (very likely) with a score of 4.
- Step 2: Determine what the consequences are. This step assesses the consequences in terms of safety and serviceability, assuming the given damage modes occur. It categorizes the potential consequences into four *consequence factors* ranging from low (minor effect on serviceability) with a score of 1 through severe (e.g., collapse, loss of life) with a score of 4.
- Step 3: Determine the inspection interval and scope. The occurrence factor and consequence factor are used to assess the inspection interval and the scope of the inspection, considering the potential damage modes that are likely to occur.

The reliability matrix (Figure 4-1) illustrates that inspection intervals should be shorter if the occurrence and consequence factors are high and may be longer if the occurrence and consequence factors are low.



Source: *NCHRP Report 782: Proposed Guideline for Reliability-Based Bridge Inspection Practices.*

Figure 4-1. Reliability matrix for determining maximum inspection intervals for bridges.

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. Specific preservation actions may be identified by tunnel operations personnel when a piece of equipment malfunctions; by specialty companies when providing troubleshooting and testing of equipment or systems; by agency/consultant personnel after completion of walk-through, periodic, or in-depth inspections; and by the agency/consultant after performing code evaluations to identify actions needed to comply with current codes and standards. A code evaluation may trigger the need for installation of entirely new systems within the tunnel, such as life safety systems that are needed in the event of a fire.

A complete list of preservation actions should be developed as part of an asset management process. Alternative preservation actions that might resolve a particular issue can be included and ultimately compared using the metric described in Chapter 5. The information critical for comparing preservation actions includes:

- Tunnel identification,
- Capital cost (the initial cost of the preservation action in present-value dollars; includes labor and equipment),
- Annual change in cost (e.g., savings in energy or maintenance),
- Average daily traffic,
- Theoretical service life of the asset,
- Remaining life of the asset prior to the preservation action being implemented,
- Condition of the existing asset prior to the preservation action being implemented,
- Whether the improvement is driven by a regulatory requirement or industry standard, and
- Risk of unplanned events.

Once this information has been established, the AAMT can use it to evaluate priorities based on element condition and associated risks of failure, can develop and consider various funding scenarios, and can forecast staffing needs as identified in Chapters 5, 6, and 7.

4.3 Examples of Tunnel Preservation Actions

To assist tunnel owners in fully understanding typical preservation actions required for aging tunnel systems, this section summarizes some typical tunnel system conditions that, once identified, an owner needs to address.

Consider an agency ("Agency X" used throughout this guide) with six tunnels with varying traffic volumes. Upon completion of its normal in-depth inspection of each tunnel, it was clear that improvements were needed. The structures ranged in structural condition from fair to poor, and the life safety and lighting systems were deemed obsolete by modern standards. The agency identified numerous preservation actions:

- Making structural repairs of the tunnel walls,
- Upgrading the electrical systems,
- Replacing lighting systems,
- Rehabilitating the existing mechanical systems (fans/motors/drives),
- Cleaning and repairing all damper doors,
- Adding a new fiber-optic system,
- Installing CCTV cameras,
- Evaluating and implementing flood protection measures, and
- Overhauling the over-height truck detection system.

Since major improvements were envisioned, the agency investigated possible improvements to upgrade life safety systems to comply with NFPA 502. These included:

- Upgrades to the CO detection system,
- Addition of a heat detection system for fire events,
- Installing emergency signage providing distances to cross-passageways and exits,
- Installing new call stations,
- Providing alarms at all doors for security and detection at the operations center of security breaches,
- Adding a dry standpipe system for fire, and
- Potentially removing the tunnel ceiling to upgrade the ventilation system from semi-transverse to longitudinal ventilation.

A summary of Agency X's tunnels, including a tunnel identification number, ADT (in thousands), and a brief description, is provided in Table 4-1. A total of 32 preservation actions were identified based on the routine inspection of these six tunnels. To illustrate the range and nature of these actions, a selection of these preservation actions is presented in Table 4-2. For a complete list of all of Agency X's preservation actions, refer to Appendix D.

Additional examples of maintenance and preservation actions for numerous types of tunnel equipment are identified in Appendix B: Catalog of Preservation Actions.

Table 4-1. Agency X's tunnels.

Tunnel #	ADT (x1000)	Description
1	40	Rural tunnel on a major Interstate
2	100	High-traffic urban tunnel downtown in a major city
3	30	Low-traffic urban tunnel outside of city
4	19	Very-low-traffic urban tunnel downtown
5	50	Moderately high-traffic tunnel near Tunnel 2
6	75	High-traffic urban tunnel accessing a major city in close proximity to the river

Table 4-2. Agency X's preservation actions.

Preservation Action	Tunnel #
Ventilation upgrade to meet NFPA 502	1
Install new light-emitting diode (LED) lights	1
CO system – repair to operating condition	2
Repair active leak in tunnel	4
Remove existing concrete tunnel ceiling	6
Install flood gates	6

CHAPTER 5

Measuring Effectiveness of Preservation Actions

5.1 Evaluating Alternative Preservation Actions

To evaluate the effectiveness of a proposed tunnel preservation action, several factors must be considered. 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?

While each of these considerations plays into the final prioritization made by tunnel owners, the final prioritization is often fairly subjective since the improvements vary significantly from a structural improvement to a tunnel system improvement. Furthermore, many agency bridge/tunnel departments are led by structural engineers who understand the needs of bridges and the tunnel structure itself, but tunnels are complex facilities that involve multiple mechanical and electrical systems that must also be considered. Evaluating preservation actions to determine priorities can be a daunting task when many of the improvements needed are in different systems. This chapter presents a strategy for measuring the effectiveness of preservation actions to facilitate comparisons of different improvements.

5.1.1 Risk Assessment, Management, and Mitigation Strategies

Tunnel owners regularly assess risk when evaluating tunnel preservation actions, whether making long-term decisions on equipment needs or structural improvements. Risk mitigation often has a direct impact on the safe operation of the tunnel, but risk must also be considered in terms of operational reliability, preservation, and the other agency goals. For example, the longer a piece of equipment goes without needed repairs due to lack of funds for replacement or rehabilitation, the greater its chance for failure. Its failure could result in an unsafe condition for the traveling public or require closure of the tunnel until repairs are made, or additional costs in maintenance of the equipment could result if it is left in its present condition. Similarly, the longer water leakage occurs within a tunnel, the greater the likelihood of further structural deterioration and the possibility of unsafe conditions for the traveling public. Without remediation, water infiltration may lead to extensive costs to repair deterioration of the structure and appurtenances and to eliminate the water problem. The 2011 *AASHTO Transportation Asset Management Guide* provides guidance for transportation agencies on this subject, recommending that they consider performing risk assessment and risk management as well as develop mitigation strategies as part of the routine business functions of the agency.

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 driver, expressed as a probability, or range of probability, of an event.
- Consequences to the asset, a categorization of the damage or loss of function of the asset, 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 damage or loss of function caused by the extreme event.[5]

A typical risk management framework was presented in the 2011 *AASHTO Transportation Asset Management Guide* and is shown in Figure 5-1.

Owners should consider likelihood, consequences, and impact when evaluating risk. The level of risk can be categorized as low, moderate, high, and extreme, as shown in Figure 5-2 and as defined in the 2011 *AASHTO Transportation Asset Management Guide.*

The asset management approach presented in this chapter suggests that owners evaluate risk and risk mitigation strategies for each preservation action as part of developing the various scores described in this chapter. These strategies should be promulgated by the AAMT and can serve as supporting data explaining why preservation actions are necessary when communicating the needs to taxpayers or public officials.

5.2 Agency Levels of Service and Performance Goals

As discussed in Chapter 3, each agency will have its own set of goals or its own specific LOSs. Preservation actions that focus on these LOSs may be given higher priority than those that do not because they assist in meeting the overall goals. In addition, certain LOSs will be more important

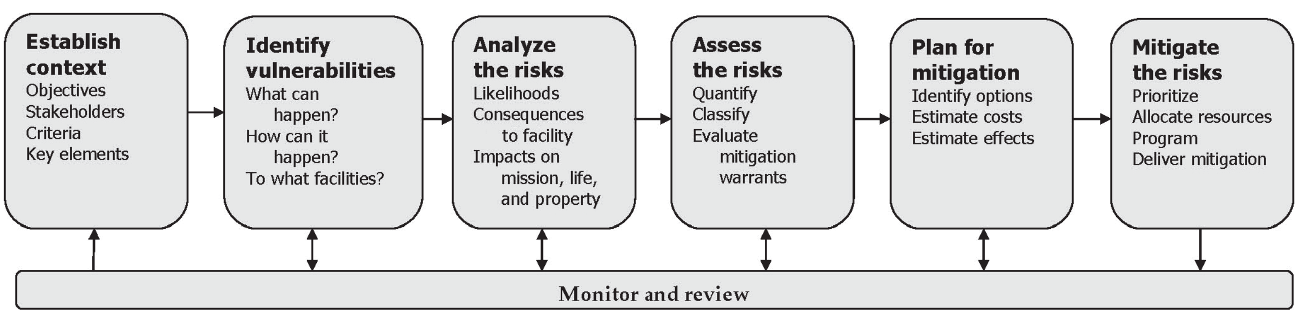


Figure 5-1. Typical risk management framework.

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

Figure 5-2. Risk likelihood and consequence categories.

within the agency than others. For example, safety and preservation are two goals that typically rank higher than other LOSs for most highway agencies. One way to quantify how well a preservation action improves the service level is to simply provide a score based on expert judgment or a qualitative assessment of its impact on performance. The LOS score would be one factor contributing to the overall effectiveness of the preservation action. The examples that follow explain the process used to develop an LOS score for each preservation action.

5.2.1 Weighting the Levels of Service

The AAMT will set relative weights for each LOS selected as part of determining an LOS score. Section 3.2 identified and described 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. When all LOS standards are identified, the tunnel owner should assign an importance percentage to each LOS such that the total percentage for all LOS standards is 100%. These percentages serve as the weights.

For setting percentages, the AAMT will rank in general order of importance from highest to lowest among the LOS standards for the tunnel at the time of the ranking. Agency X's AAMT ranked the order of importance as: safety, reliability, preservation, quality of service, security, and environment. The ranking should reflect the long-term strategic directions of the agency. Factors influencing the establishment of this order could be as follows:

- Safety was at the top of the AAMT's evaluation when they considered the following factors: A number of accidents have 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 in weighting as part of the asset management approach. This resulted from a series of unexpected events causing tunnel closure for a significant period of time. 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, and 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 were complaining about the light levels present when they entered the tunnels and infiltrating 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 by the AAMT 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 result in security being less important than the other LOS standards.
- Environment was ranked sixth since there have been few, if any, threats to the environment from the agency's tunnels. Possible environmental concerns might include the draining of

spills within the tunnel to local streams, exhausting of tunnel emissions 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 consideration of ranking should continue within the AAMT until all members are in agreement with the ranking of LOS elements in order of importance.

While developing the LOSs for its six tunnels, the AAMT agreed that improvements having a very high impact on safety should have priority above all others. Therefore, the agency has chosen to make repairs and improvements that "greatly" or "significantly" affect safety prior to other repairs and improvements. The remaining levels of service were assigned weights to total 100%, with reliability and preservation ranking second and third, respectively, after safety. The weights were assigned by the AAMT after ranking agency goals and are as shown in Table 5-1. When resulting LOS weights are less than or equal to 5%, the agency should evaluate whether to include those LOSs. In the case of this example, the agency should evaluate whether to include LOSs for security and environment.

5.2.2 Assessing the Impact of Preservation Actions on LOS

Each preservation action will affect the agency's ability to achieve the selected LOS, and this impact must be captured in the prioritization process. To weigh the relative impact of preservation actions, each improvement must be evaluated with respect to each LOS. To evaluate how well an action addresses each LOS, a rating of 1 to 5 might be used, where a 5 indicates that the preservation action will greatly improve the performance associated with the LOS, and a 1 indicates that the preservation action will have very little impact. For each LOS, Table 5-2 defines the intent of the ratings 1 through 5. A rating of 0 would be used if the LOS was not applicable for that preservation action.

The ratings are based on the subjective judgment of the tunnel owners' 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. For each of the agency's selected preservation actions (see Section 4.3), LOS ratings are assigned as shown in Table 5-3. The rationale for selection of the LOS ratings for each of the preservation actions is provided in the following.

- Ventilation upgrade to meet NFPA 502: Consulting Table 5-3, upgrading the existing aging ventilation greatly affects safety and preservation, but has very little impact on reliability (keeping the tunnel open to traffic), security, and quality of service. Appropriately, safety and preservation are assigned a rating of 5, and reliability, security, and quality of service are assigned a rating of 1. No environmental impact is anticipated from this improvement.
- Install new light-emitting diode (LED) lights: The lights in Tunnel 1 are corroded and near the end of their service life; if not replaced soon, they run the risk of falling off the walls. Therefore, installing new light fixtures will significantly affect safety, and improved light levels will improve quality of service; these levels of service are assigned a rating of 4. After an analysis of alternative lighting, it was decided that LED fixtures should be installed. Removing the existing lights and installing the new ones greatly affects preservation, and this LOS is assigned a rating of 5. LED lights are much more energy efficient than the existing lights, and therefore the score for

Table 5-1. Level-of-service weights.

LOS	Reliability	Safety	Security	Preservation	Quality of Service	Environment
Weight (%)	20	40	5	18	15	2

Table 5-2. Level-of-service ratings.

Ratings \ LOS	Reliability	Safety	Security	Preservation	Quality of Service	Environment
	The improvement will have very little…					
1	…impact on the ability to keep the tunnel open and operational.	…impact on safety of workers or the traveling public.	…impact on the vulnerability to technological or natural hazards.	…effect on the remaining life of the asset.	…effect on the experience for the driving public.	…impact on the environment.
	The improvement will somewhat…					
2	…affect the ability to keep the tunnel open and operational.	…affect safety of workers or the traveling public.	…affect the vulnerability to technological or natural hazards.	…increase the remaining life of the asset.	…improve the experience for the driving public.	…affect the potential for environmental impacts.
	The improvement will moderately…					
3	…improve the ability to keep the tunnel open and operational.	…improve safety of workers or the traveling public.	…reduce the vulnerability to technological or natural hazards.	…increase the remaining life of the asset.	…improve the experience for the driving public.	…reduce the impacts or potential for environmental impacts.
	The improvement will significantly…					
4	…improve the ability to keep the tunnel open and operational.	…improve safety of workers or the traveling public.	…reduce the vulnerability to technological or natural hazards.	…increase the remaining life of the asset.	…improve the experience for the driving public.	…reduce the impacts or potential for environmental impacts.
	The improvement will greatly…					
5	…improve the ability to keep the tunnel open and operational.	…improve safety of workers or the traveling public.	…reduce the vulnerability to technological or natural hazards.	…increase the remaining life of the asset.	…improve the experience for the driving public.	…reduce the impacts or potential for environmental impacts.

Table 5-3. Level-of-service ratings for selected preservation actions.

LOS		Reliability	Safety	Security	Preservation	Quality of Service	Environment
Weights		20%	40%	5%	18%	15%	2%
Preservation Action	Tunnel #						
Ventilation upgrade to meet NFPA 502	1	1	5	1	5	1	N/A
Install new LED lights	1	3	4	2	5	4	5
CO system – repair to operating condition	2	2	5	N/A	4	N/A	2
Repair active leak in tunnel	4	4	5	N/A	5	5	N/A
Remove existing concrete tunnel ceiling	6	4	5	N/A	4	5	N/A
Install flood gates	6	4	4	N/A	5	N/A	N/A

environment is a 5. Although the current system provides the needed lighting levels to operate the tunnel, a failure could require tunnel closure, so reliability is assigned a 3. Due to the rural location of Tunnel 1, the new lights have little impact on security.

- CO system—repair to operating condition: The existing CO system needs to be repaired to make it operational. Repairing the system greatly affects safety, and therefore this LOS receives the highest possible rating. Additionally, the service life of the asset may be extended after the repairs, so it has a significant impact on the preservation LOS. It has little impact on the ability to keep the tunnel open and operational, and has little impact on the environment.
- Repair active leak in tunnel: There is a significant leak in Tunnel 4's arch, which is causing deterioration of the structure and development of icicles in the winter months. Repairing the leak is needed to eliminate the cause of deterioration and to increase the service life of the structure; thus, preservation is rated a 5. Elimination of the infiltration will greatly increase the safety of the traveling public, since the current problem includes the possibility of falling icicles or slippery pavement. It will also eliminate the closures needed to remove icicles or delaminated concrete. While this preservation action may reduce the number of customer complaints about water dripping on their vehicles, repairing the leak has no effect on security levels or the environment.
- Remove existing concrete tunnel ceiling: Tunnel 6 is located in an urban area and has significant traffic during peak hours. The tunnel has minimal horizontal and vertical clearances, and traffic typically slows significantly through the tunnel as a result. The ceiling has deteriorated through the years, and portions have been replaced at various times. Removing the existing tunnel ceiling will greatly affect the quality of service for motorists by improving the sense of openness and improving clearance and is anticipated to have a significant impact on the flow of traffic (reliability) through the tunnel. By eliminating the ceiling, safety is also greatly improved. Although the existing ceiling was recently repaired, the possibility of future spalling of the concrete will be eliminated with the ceiling's removal. Removing the ceiling significantly affects the overall preservation of the tunnel by eliminating any future tunnel issues related to the existing deteriorated ceiling. The security and environment LOSs are not affected by this improvement.
- Install flood gates: Installing flood gates has the potential to greatly affect the life of the tunnel and significantly improve safety. During a flood event, the gates will protect the tunnel structure and systems from damage and workers from dangerous conditions. The gates will allow the tunnel to be opened immediately after flood events since flooding of the tunnel and damage to its systems will be prevented. Therefore, it has a significant effect on reliability. No impact is expected on security, quality of service, or the environment.

5.2.3 Calculating the LOS Score

The overall LOS score for each preservation action reflects the impact of the improvement on the agency LOS goals. The initial step is to identify the LOSs and their relative importance as defined in Section 5.2.1. Weights should be applied to each LOS, totaling 100%, based on the overall evaluation of their entire transportation network goals. This exercise may require considerable discussion among AAMT members until they arrive at percentages agreed upon by all members. The next step involves rating each preservation action's impact on the performance associated with each rating as presented in Table 5-3.

The aggregate LOS score can then 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:

$$\text{LOS} = \left(W_R * R + W_{S_a} * S_a + W_{S_e} * S_e + W_P * P + W_Q * Q + W_E * E\right)/5 \qquad \text{Equation 5-1}$$

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, and

W_R, W_{S_a}, W_{S_e}, W_P, W_Q, W_E = weights for reliability, safety, security, preservation, quality of service, and environment scores, where $(W_R + W_{S_a} + W_{S_e} + W_P + W_Q + W_E) = 100$.

As discussed in Section 5.2.1, the AAMT decided to focus its priorities on actions that significantly and greatly affect safety (LOS ratings of 4 and 5). Table 5-4 shows a summary of ratings and final LOS scores for a selection of actions that have the desired impact on safety. Due to the high weighting of safety, the final LOS scores are, at a minimum, moderately high. Reliability and preservation are ranked second and third and are weighted similarly. Therefore, actions that affect safety, reliability, and preservation produce the highest LOS scores. Likewise, actions that have the least impact on safety, reliability, and preservation produce the lowest LOS scores.

LOS score evaluations for all of Agency X's preservation actions are included in Appendix D.

5.2.4 Calibrating the LOS Score

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

Table 5-4. Preservation action ratings and LOS score.

LOS		**Reliability**	**Safety**	**Security**	**Preservation**	**Quality of Service**	**Environment**	**LOS Score (Eq. 5-1)**
Weights		20%	40%	5%	18%	15%	2%	
Preservation Action	**Tunnel #**							
Ventilation upgrade to meet NFPA 502	1	1	5	1	5	1	N/A	**66.0**
Install new LED lights	1	3	4	2	5	4	5	**78.0**
CO system – repair to operating condition	2	2	5	N/A	4	N/A	2	**63.2**
Repair active leak in tunnel	4	4	5	N/A	5	5	N/A	**89.0**
Remove existing concrete tunnel ceiling	6	4	5	N/A	4	5	N/A	**85.4**
Install flood gates	6	4	4	N/A	5	N/A	N/A	**66.0**

Note: A rating of 0 is used when the LOS is not applicable for that preservation action.

affect the resulting LOS score and, therefore, should be established by the AAMT and used consistently. As indicated in Section 5.1, the AAMT should follow a process where the LOSs are prioritized, and then individual weights are applied to each. An adjustment in the weights by a few percentage points up or down will result in similar variability in the resulting scores because an ultimate increase in one LOS weight requires a decrease in another to maintain a sum of 100.

Similarly, there is a large degree of subjectivity in the assignment of LOS ratings for each preservation action. It is recommended that the ratings be assigned by a technical team having specific knowledge of each of the improvements so that each preservation action can be accurately assessed for its impact on the LOS. The scoring from 1 to 5 was selected to limit the possible variations yet capture the variability. A smaller range of scores would have a larger impact on variability of the overall score, and a larger range of scores would make it difficult to differentiate between scores. It is likely that a preservation action considered to improve the LOS would be assigned a 4 or 5 if it were deemed to have a major impact, and a 1 or 2 if it would have little impact. Therefore, the variability in scoring, if the technical team has adequate knowledge of the improvement, should only result in a one-point difference in ratings. Since the highest weight possible for an LOS is 100%, the largest variation in LOS score for a one-point difference would be 20%. Since multiple LOSs will usually be assigned with varying weights, this helps to aggregate the scores. A one-point difference in LOS rating will therefore not usually result in a significant difference. In the example noted in Table 5-4, safety is weighted the highest (40%). For the ventilation improvement noted, a reduction in the safety rating from 5 to 4 would result in an LOS score of 58.0, a 12% reduction from the score of 66.0. Obviously, the greater the change in the product of LOS rating times LOS weight, the greater the variation in the overall score.

5.3 Cost-Effectiveness

Cost plays a significant role in the comparison of tunnel maintenance and repair actions and in prioritizing actions for implementation. Tunnel owners will often implement improvements that are the least expensive 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.

To compare alternatives using cost, life-cycle costing is typically used since it allows initial costs to be tempered by potential savings in maintenance and energy over the life of the asset. 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 of time, such as 50 years. Alternatively, the LCC could be annualized over the service life to compare the costs per year.

Another factor that plays into the decision of preservation action implementation is the number of users that will be affected. A given improvement could have a high initial cost, but its impact would be felt by a large number of users of that particular tunnel. In this context, it is necessary to consider costs in terms of cost per user. Accordingly, improvements that have lower costs per user should receive higher priority. The ADT is used in the calculation of cost per user. This section provides a means of calculating a cost-effectiveness score to facilitate comparison of alternatives.

5.3.1 Life-Cycle Cost

Life-cycle costing is a critical factor in the planning for future upgrades and repairs. LCCs are used to make decisions based on the life of an asset, incorporating possible cost savings or other costs that occur at a future date during the asset's service life. It is beneficial to use LCC analysis when evaluating alternative approaches, whether alternative equipment or varying options for rehabilitation, to ensure the greatest cost efficiency over the life of the tunnel. This process involves evaluating the alternatives over a given duration or economic life to determine specific costs involved for each option and then equating them through a series of mathematical formulas that enable the costs of each option to be compared at a common point in time. A good reference on life-cycle costing analysis is FHWA's *Life-Cycle Cost Analysis Primer.*(14)

The LCC of a given alternative includes all associated costs over the expected life of the option. In general, these costs may include:

- Initial costs: Project cost, including equipment and material costs, construction costs, and engineering or design costs.
- Operating/energy costs: Annualized cost to operate (e.g., cost of electricity to run mechanical equipment, reduction in staff costs due to automation). These could be extra expenses or savings as compared to other alternatives such as the no-build alternative.
- Maintenance costs: Annualized cost for maintenance.
- Rehabilitation costs: Future expense for known procedures at a specified time (e.g., replacement of lamps, drivers/ballasts in lighting).
- User costs: Costs associated with impact on the functioning of the tunnel (e.g., tunnel may need to be shut down for repair; therefore, impact to traffic can be shown by applying an annualized cost to each hour the tunnel is closed).
- Salvage value: Sale value of equipment at the end of its service life (e.g., a mechanical fan may be of some value to others even after it has served its purpose in the tunnel).

The data used for life-cycle cost calculations should be carefully considered. There is uncertainty when predicting the expected life and associated costs for an asset because there are many factors that affect asset function and costs. However, if quality information is used to evaluate each preservation action, then there is similar uncertainty among all actions allowing for an acceptable comparison of actions based on life-cycle costs.

Evaluating LCC for different systems and tunnel elements with a wide range of service lives requires a common baseline for comparison. Calculating the present value (PV) of different preventive actions or alternatives allows owners to account for the future value of their investments and associated maintenance and energy costs or savings. If all preventive actions were on the same time scale (i.e., all actions extended the remaining life by 20 years), then all could be compared using only the calculated present value. However, when actions extend the remaining life by different values, an annualized life-cycle cost is a more appropriate comparison measure. Two methods for performing a LCC analysis, the present worth method and the annualized method,(15) are outlined in the following.

5.3.1.1 Present Worth Method

As the name implies, this method attempts to bring all of the present and future costs of a given option to present-day values. This process should be completed for each major repair/rehabilitation, and subsequently the present worth costs for each could be compared. Determining the present worth of a future expense is done by taking into account the time value of the money and, therefore, discounting the amount by a predetermined rate (discount rate) over the period between the future expense and the present time. The present worth of the future expense is also the amount that could be invested today with reinvested interest over the duration to equal the amount of the future expense. An example of a future expense might be the cost to rehabilitate a piece of equipment that is being evaluated for replacement. The general form of the equation for determining the present worth of a future expense is:

$$P = F\left[\frac{1}{(1+i)^n}\right] \qquad \text{Equation 5-2}$$

where

P = present worth,
F = future one-time expense,
n = number of years, and
i = discount rate.

Future expenses can also be uniform, in that the same expense occurs at the end of each year. An example of this would be the annualized maintenance costs described previously. The general form of the equation for determining the present worth of an end-of-year expense is:

$$P = A\left\{\frac{\left[(1+i)^n - 1\right]}{\left[i(1+i)^n\right]}\right\} \qquad \text{Equation 5-3}$$

where

P = present worth,
A = end-of-year payments,
n = number of years, and
i = discount rate.

5.3.1.2 Annualized Method

The annualized method is used to transform present and future costs into a uniform annual expense. This annual expense can be compared to the annual expenses of the other repair/rehabilitation alternatives to determine which is most cost-effective. Converting all future expenses into a present value as before and then using Equation 5-4 to convert that value into an annual expense will provide a uniform annual cost.

$$A = P\left\{\frac{\left[i(1+i)^n\right]}{\left[(1+i)^n - 1\right]}\right\} \qquad \text{Equation 5-4}$$

where

P = present worth,
A = end-of-year payments,
n = number of years, and
i = discount rate.

The cash-flow diagrams in Figure 5-3 illustrate the annualized method. The annualized method allows for a simplified comparison of two preservation actions with different expected service lives (n, number of years) without having to use the same time scale for each preservation action. The cash-flow diagrams use the year-end convention, where it is assumed that all cash flows take place at the end of the year in which they occur (A, end-of-year payments). Once the equivalent annualized payment (A_{eq}) is determined for each action, the costs may be compared since consideration of the time scale is no longer required.

Figure 5-3(a) displays the initial cash flow for a selected preservation action, including the capital cost to implement the action, the annual change in costs per year, and a future one-time cost. The future one-time cost is moved to the present in Figure 5-3(b) using Equation 5-2 (P given F). In Figure 5-3(c), the annual change in costs is also moved to the present (P given A) with Equation 5-3. Finally, in Figure 5-3(d), the present value of all of the cash flows is transformed into an equivalent annual cash flow (A given P) using Equation 5-4.

These methods can also be performed using factors available from standard economic tables that are based on the discount rate and the economic life under consideration. These

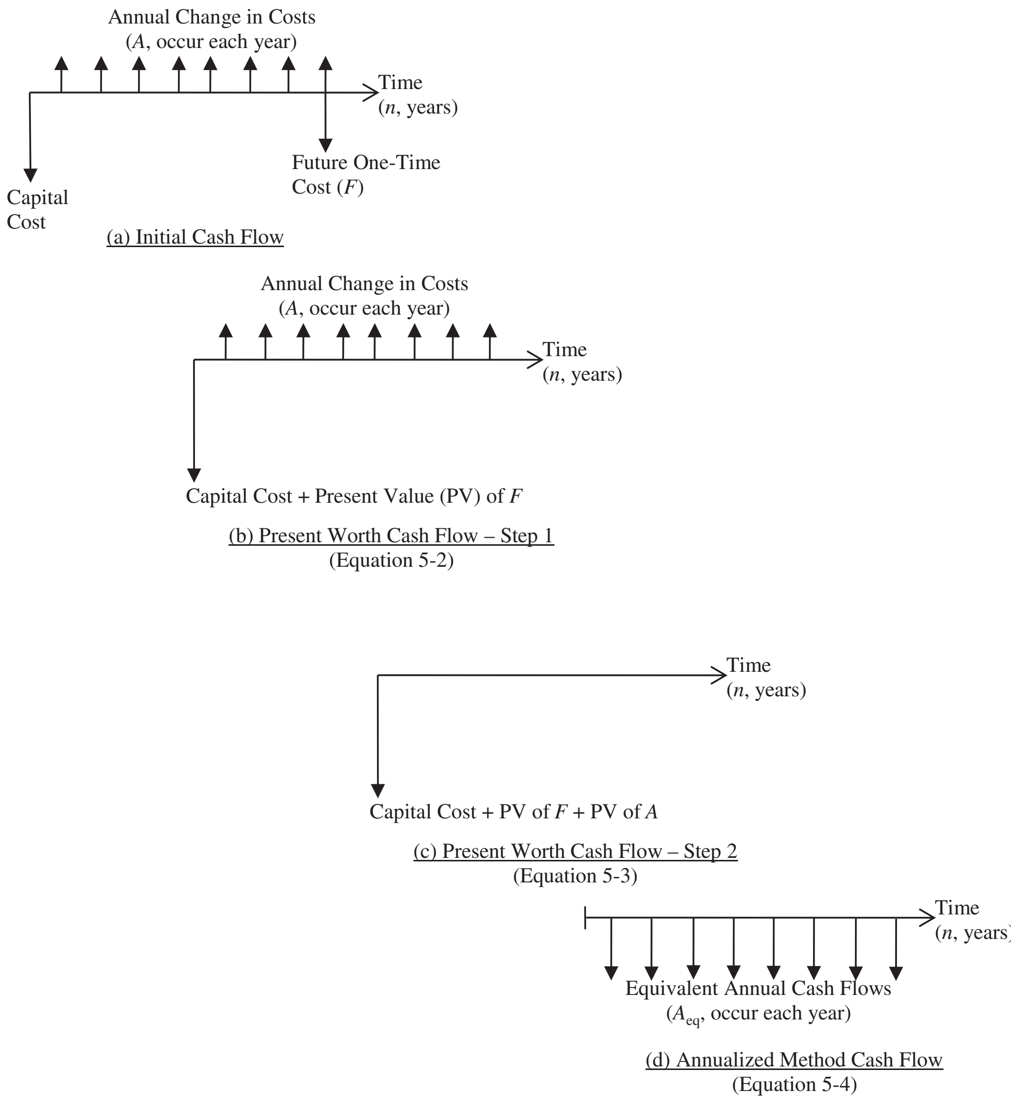


Figure 5-3. Annualized method.

factors are also unique to the desired result. The procedure for using standard economic tables is as follows:

- Determine the discount rate (i) and economic life (n) to be used for the analysis. It is important to choose an economic life that is equal for the given alternatives if the present worth method is to be used. Otherwise, the annualized method must be used.
- Develop a cash-flow diagram for each option that shows all relevant costs described previously on a timeline of years in the economic life.
- Take individual costs, whether uniform or one-time, and insert them in the proper formula given previously along with the factor from the appropriate economic table.
  - (P/F, i%, n)—or present worth (P) given future expense (F) at discount rate (i) for number of years (n).
  - (P/A, i%, n)—or present worth (P) given end-of-year payments (A) at discount rate (i) for number of years (n).
  - (A/P, i%, n)—or end-of-year payments (A) given present worth (P) at discount rate (i) for number of years (n).

5.3.1.3 Discount Rate

Caution should be taken when determining the appropriate discount rate. Because of the power of compounded interest, a difference in discount rate can actually change the final outcome of the analysis if the repair/rehabilitation options being considered have different arrangements of uniform and one-time costs. According to the FHWA draft report, *A Discussion of Discount Rates for Economic Analysis of Pavements*:

> The discount rate can affect the outcome of a life-cycle cost analysis in that certain alternatives may be favored by higher or lower discount rates. High discount rates favor alternatives that stretch out costs over a period of time, since the future costs are discounted in relation to the initial cost. A low discount rate favors high initial cost alternatives since future costs are added in at almost face value. In the case of a discount rate equal to 0, all costs are treated equally regardless of when they occur. Where alternative strategies have similar maintenance, rehabilitation, and operating costs, the discount rate will have a minor effect on the analysis and initial costs will have a larger effect.(16)

For the purposes of this example, the discount rate was assumed to be 3%, reflecting the anticipated average time value of money used for the analysis. The tunnel owner may elect to use the current national discount rate used by its agency for its calculations.

5.3.1.4 Life-Cycle Cost Example

For Agency X's preservation actions, the various cost elements making up each improvement must first be estimated, including the annual costs (potential savings) that apply over the service life of the improved asset. Table 5-5 shows the LCC analysis for the six preservation actions; the present worth of each action is calculated as an intermediate step for computing the annualized cost in the next section.

Table 5-5. Changes in annual costs and present value of LCC.

Preservation Action	Tunnel #	Capital Cost ($)	Agency Oversight Cost ($)	Annual Energy Cost Savings ($)	Annual Change in Maintenance Cost ($)	Total Annual Change in Costs ($)	Service Life of the Asset After Improvement	PV of LCC ($)**
Ventilation upgrade to meet NFPA 502	1	5,700,000	570,000	–150,000	–2,500	–152,500	25	3,614,495
Install new LED lights	1	3,400,000	136,000	–66,000	–5,000	–71,000	20	2,479,699
CO system–repair to operating condition	2	32,000	3,200	0	0	0	20	35,200
Repair active leak in tunnel	4	10,000	1,000	0	0	0	20	11,000
Remove existing concrete tunnel ceiling	6	8,000,000	800,000	0	–20,000*	–20,000*	50	8,285,405
Install flood gates	6	8,000,000	320,000	0	0	0	100	8,320,000

*Negative net change in annual cost denotes a cost savings. **PV of LCC is calculated based on the service life of the asset after the improvement is implemented.

The initial cost of the improvement is estimated based on the labor, equipment, and materials required to complete the work. In addition to these costs, the agency will have internal costs. These include, at a minimum, internal staff labor associated with managing, overseeing, and inspecting the work. The staffing section in Chapter 7 provides a method of estimating agency oversight costs. To capture the costs over the life of the asset to facilitate comparisons of the alternatives, the annual costs and future costs must be included. Table 5-5 highlights the annual energy savings associated with the ventilation upgrade and new LED lights as well as the savings in maintenance costs if the ceiling is removed permanently. Once the costs are estimated, the present value of all costs can be calculated using the present worth formulas in Section 5.3.1.1. It should be noted that the present value in the example is calculated using the service life after implementing the preservation action; to compare LCC directly at this point, the present value would need to be calculated based on a common time period, such as 100 years. However, the present values in Table 5-5 are used to calculate the annualized costs in Table 5-6.

5.3.2 ADT—The Effect of the Number of Users

When an agency's tunnels are located both in urban areas with high traffic volumes and in rural areas with significantly less traffic, prioritizing preservation actions is complicated. The risk of not implementing a preservation action will be higher for the urban tunnel due to the greater number of users. For example, a problem with Tunnel 2, located in an urban area with ADT of 100,000 vehicles, would have a greater impact than a problem with Tunnel 1 with 40,000 vehicles per day in a rural area on an Interstate. The risk of safety-related incidents would be greater in

Table 5-6. Cost-effectiveness scores.

Preservation Action	Tunnel #	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)
Ventilation upgrade to meet NFPA 502	1	5,700,000	570,000	–152,500	3,614,495	25	40	207,573	5.19	**1.9**
Install new LED lights	1	3,400,000	136,000	–71,000	2,479,699	20	40	166,675	4.17	**2.4**
CO system – repair to operating condition	2	32,000	3,200	0	35,200	20	100	2,366	0.02	**100.0**
Repair active leak in tunnel	4	10,000	1,000	0	11,000	20	19	739	0.04	**100.0**
Remove existing concrete tunnel ceiling	6	8,000,000	800,000	–20,000	8,285,405	50	75	322,016	4.29	**2.3**
Install flood gates	6	8,000,000	320,000	0	8,320,000	100	75	263,300	3.51	**2.8**

Notes: Discount rate = 3%; cost factor *F* = 10.

Tunnel 2 for a given preservation action focused on improving safety if it is not implemented than for the lower-ADT Tunnel 1. The impact of having to close the tunnel would be greater for Tunnel 2 than Tunnel 1 due to the higher number of users. Therefore, the number of users affected by a preservation action should be taken into consideration when evaluating cost-effectiveness. ADT data, which are typically collected by most agencies for their tunnels, afford a convenient measure for the number of users.

As previously discussed, annualizing the LCC allows the user to compare actions with varied impacts on asset remaining life. Using the LCC and the ADT for the tunnel, an estimate of cost per user can be calculated and used to assess the cost-effectiveness of the preservation action.

5.3.3 Calculating the Cost-Effectiveness Score

Improvements with the lowest cost per user are considered to be most cost-effective. To calculate the cost per user, LCC must be assessed and annualized. Therefore, for each preservation action, the following items are needed to calculate the CE score:

- Capital cost (the 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)—used to add agency costs to overall project cost;
- Change in annual costs considering energy, maintenance, closures, reduction in accidents, reduction in staff, and so forth;
- ADT; and
- Service life after improvement—the number of years to which the annualized cost applies.

The annual life-cycle cost (ALCC) is computed as follows:

$$\text{ALCC} = C * \left[i * (1+i)^n \right] / \left[(1+i)^n - 1 \right] - A \qquad \text{Equation 5-5}$$

where

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

The cost-effectiveness of the preservation action is inversely proportional to the cost per user. Accordingly, the reciprocal of the cost per user is used as an initial step in determining the CE score (yielding users per net dollar invested). Due to the range of possible costs for preservation actions and ADTs for tunnels, the resulting score has significant variability. To facilitate combination with the other scores to obtain an overall MOE for each preservation action, the CE score must be between 0 and 100. However, for low-cost improvements, particularly those in high-traffic tunnels, the resulting score can far exceed 100. For these cases, a maximum score of 100 is assigned. Through evaluation of many preservation action examples, the following equation was developed for the CE score:

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

Equation 5-6

$$\text{CE} = 100/[(\text{ALCC}/\text{ADT}) * F]$$

where

CE = cost-effectiveness score,
ADT = average daily traffic, number of vehicles,
ALCC/ADT = annual life-cycle cost per daily vehicle, and
F = cost factor, varies (see Section 5.3.4).

As shown in Table 5-6, the low cost of the repairs to the CO system and the active leak in the tunnel, when calculated directly, would exceed 100. Therefore, the CE score is limited to the maximum value of 100 for these improvements.

5.3.4 Calibrating the CE Score

Because Equation 5-6 is normalized to result in CE scores that range between 0 and 100, it must be validated for typical preservation actions. This is essential to ensure practical scores that are distributed over a distinguishable range between 0 and 100 and that offer an accurate and fair assessment of cost-effectiveness.

For the values provided in Table 5-6, a value of 10 was assigned as the cost factor *F* in Equation 5-6. This number was selected based on the sample data for Agency X's preservation actions and will require examination with any new set of data or significant changes to the records. Since the score is directly related to only the annual cost per daily vehicle, score equation calibration can be achieved through adjusting the cost factor variable to provide meaningful scores that:

- Are distributed relatively evenly from 0 to 100,
- Prevent too many repeat scores of 0 or 100, and
- Properly reward actions that have low capital costs and affect a large number of vehicles.

The cost factor variable *F* represents a scaling factor and allows the agency to adjust the CE score equation to best fit its preservation action costs. For example, an agency with a high number of expensive actions may determine that a cost factor equal to 20 best distributes its actions. An agency with less expensive actions may determine that a cost factor equal to 2 better fits its data. To determine the appropriate factor, it is recommended that the agency start with a cost factor of 10. Then, comparing all of its preservation actions together, if distribution is poor (within the range from 0 to 100) and too many actions are receiving a CE score of 100, the agency should incrementally increase its cost factor. If the distribution is poor and too many actions are receiving extremely low CE scores (near 0), then the agency should incrementally decrease its cost factor accordingly. Agency X chose to use a cost factor of 10 based on all of its preservation actions (presented in Appendix D). Note that while Table 5-5 shows a poor distribution of scores, these six preservation actions represent only a portion of Agency X's evaluated actions.

While an agency can theoretically use any cost factor in the CE core equation, it is important that the factor's influence on all of the preservation actions' CE scores be assessed. Arbitrarily choosing a factor without evaluating the results can lead to a poor distribution of CE scores and, therefore, an undesired impact on the overall MOE score (Section 5.5). The overall impact on the MOE score is dependent on the weight placed on the CE score. An agency placing a greater weight on cost must carefully evaluate the CE score and cost factor.

5.4 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 closure of the tunnel. There are several factors that contribute to urgency: condition, remaining life, regulatory requirements, and unplanned events.

Typically, elements in poor condition or near the end of their useful life have the greatest urgency for improvement due to the risk that exists if the improvement is not implemented. Upgrading to meet a new regulatory requirement or design standard may also be a priority for the agency. Furthermore, improvements focused on reducing risks associated with unplanned events such as floods or fires may be considered a high priority depending on the probability of the event. The RBU score, the third component contributing to the overall MOE, is determined by considering all of these factors.

5.4.1 Remaining Life Versus Service Life

When an asset is near the end of its service life, its remaining life may be evaluated to determine whether replacement is warranted. Remaining life is dependent on multiple factors, including age, condition, and maintenance history. The RBU score evaluates condition as a separate factor (Section 5.4.2), but the age of the asset and how close it is to the end of its service life must be closely examined in evaluating how urgently the preservation action is needed. Assets that have expended most of their useful service lives should receive consideration of higher priority in the rankings based on the risks associated with their failure.

For evaluation of the asset's age and to facilitate comparison of multiple assets with varying service lives, it is recommended that the percent of life expended be determined. For each preservation action, the existing asset should be evaluated prior to implementation of the preservation action since the urgency applies to the existing asset. The remaining life for the existing asset must first be determined.

There are considerable documentation and available references for obtaining service life information and calculating remaining life. While agencies may have significant experience with roadway pavement and structural repairs, it is important to accurately assess the service life of electrical and mechanical assets. The service lives for electrical and mechanical assets are highly dependent on maintenance performed, operating ambient temperature, and other environmental conditions such as the presence of moisture and dust.[17] The average expected service life for most major electrical equipment can be assumed to be approximately 40 years. Appropriate adjustments can then be made to account for performed maintenance and operating conditions. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers' (ASHRAE) *2011 ASHRAE Handbook—Heating, Ventilating, and Air-Conditioning Applications* details service life estimates in Chapter 37.[18] For tunnel systems, service life estimates are provided for centrifugal and axial fans, base-mounted pumps, motors, motor starters, transformers, and pneumatic, electric, and electronic controls. These values may also be assessed based on previous experience, historical data, or manufacturer's recommendations.

Once the remaining life and the service life are determined, the percent of life expended is easily calculated. Table 5-7 presents the calculation for the six example preservation actions. When a preservation action implements a system that did not exist in the tunnel previously, "N/A" is entered, which eliminates age as a factor in the determination of the RBU score.

5.4.2 Determining Condition

Tunnel conditions can be assessed by the tunnel operations and maintenance staff, by agency engineers, or by consultants engaged to perform in-depth condition surveys of the tunnel and its associated systems. Conditions are evaluated by any of these sources or in combination with one another to provide an assessment of the existing tunnel asset prior to developing the list of

Table 5-7. Risk of unplanned events probability.

Preservation Action	Tunnel #	Remaining Life	Theoretical Service Life	% Life Expended	Condition (1 to 4)	Regulatory Compliance Issue?	Risk of Unplanned Event Probability (1 to 3)
Ventilation upgrade to NFPA 502	1	1	25	96	2	Y	3
Install new LED lights	1	5	20	75	3	Y	1
CO system – repair to operating condition	2	2	20	90	4	Y	1
Repair active leak in ceiling	4	5	50	90	3	N	1
Remove existing concrete tunnel ceiling	6	0	50	100	3	N	1
Install flood gates	6	N/A*	100	N/A	N/A	N	3

*The condition is rated as N/A when the proposed preservation action is installing a component that is new to the tunnel system.

needed improvements. Such conditions can be established by following the guidelines of the FHWA 2015 *Specifications for National Tunnel Inventory*.

Condition states of the existing asset or tunnel system, without consideration of any improvement, should be categorized as CS1 to CS4 as follows:

- CS1—good condition,
- CS2—fair condition,
- CS3—poor condition, and
- CS4—severe condition.

This condition data should be determined at the time the list of preservation actions is developed, making the data readily available for use in calculating the RBU score. As shown in Table 5-7, CS1 to CS4 represents a condition rating of 1 through 4, respectively.

5.4.3 Regulatory Compliance

The majority of tunnels in existence today were designed before the introduction of NFPA 502 and its fire and life safety requirements. For this reason, tunnel owners are not required to upgrade to meet the standard, but many owners are upgrading to meet this standard where possible. Some owners are investigating the upgrades needed to achieve compliance for safety reasons, so these improvements may be given higher priority. Other codes or standards may also be applicable; thus, owners may be required to upgrade to meet current codes. It is therefore important to note preservation actions that are related to regulatory compliance.

As with condition data, an indication of whether the preservation action is based on a regulatory requirement should be captured when the list of preservation actions is developed. A yes (Y) or no (N) indicator is provided, as shown in Table 5-7.

5.4.4 Risk of Unplanned Events

The aftermath of Hurricane Sandy along the East Coast is evidence of the devastation that can result from unplanned events. Extreme weather, flooding, fires, and seismic events are among the many unplanned events that might occur, albeit rarely. Tunnel owners should consider the risk of these events and their possible impacts and plan for these occurrences. Preservation actions focused on resiliency may be difficult to prioritize because the future is unknown, but owners must evaluate the risks and consider these risks as another factor when developing the RBU score.

For each preservation action, the risk of potential unplanned events should be assessed and assigned a value of 1 to 3, with 1 representing a low probability and 3 representing a high probability of the event occurring.

5.4.5 Establishing the RBU Ratings and Score

As indicated, the urgency of a preservation action requires careful consideration of the many factors noted previously. For each of these factors, the associated risks of not implementing the improvement need to be contemplated. There is no simple formula to combine all of these factors; each tunnel may have different risks associated with it, based on location, physical geography, original construction, age, and so forth. Therefore, a means of considering these factors to obtain the RBU ratings and score is needed. A subjective approach is warranted where the various contributing factors are assessed, and a rating of the urgency of the improvement is assigned based on a scale of 0 to 10, where 0 represents a condition of like new with no risk, and 10 represents a critical or urgent condition (i.e., highest priority). This assessment should be performed by the AAMT, with the specific knowledge and understanding of the various systems and the risks associated with the tunnels.

While the score is determined subjectively, it must be arrived at by logically looking through the RBU considerations, including percent life expended, condition, regulatory compliance, and risk of unplanned events. Once these considerations are established, each preservation action's associated urgency can sensibly be determined (Table 5-8) as nonexistent (RBU rating of 0), low (RBU rating of 1 to 3), medium (RBU rating of 4 to 6), high (RBU rating of 7 to 9), or extreme (RBU rating of 10). Once categorized, the rating can be assigned at the bottom, middle, or top of the set range.

Table 5-8 shows how this subjective evaluation may proceed, considering the various factors that must be considered in determining the RBU ratings. Because one of the risk factors may represent a perceived major risk and be far more significant than the other factors, it is not appropriate to merely place higher emphasis based on the number of applicable risk factors. To dismiss one high rating and assign a low overall RBU rating may ignore a significant and highly probable risk. However, minor risks for multiple factors included in the evaluation may sum to a high RBU rating. For this reason, the AAMT must evaluate all the risks and consider their relative significance in assigning an RBU rating.

Table 5-8. 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

A selection of Agency X's RBU ratings is provided in Table 5-9; additional preservation actions are presented in Appendix D. The rationale for assigning each of the RBU ratings is explained in the following.

- The highest assignment made, a rating of 10, was for removal of the existing ceiling in Tunnel 6 since it is in poor condition and has exceeded its useful life. It represents a significant risk due to the deterioration of the ceiling and is a safety hazard to the public traveling beneath it.
- The ventilation upgrade in Tunnel 1 was assigned an RBU rating of 8. While the existing ventilation system is in fair condition, it requires continuous maintenance, the equipment is getting very old, and parts are becoming difficult to find. Agency X wants to upgrade it to meet NFPA 502 to improve ventilation during a fire event, making this a regulatory compliance issue.
- Both the CO system (Tunnel 2) and active leak (Tunnel 4) repairs were assigned an RBU rating of 7 due to the condition and age of these assets. Since the CO system is currently non-operational, it received a severe condition rating. Tunnel 4 is in poor condition due to active leaks that represent a significant safety risk, especially during months when freezing occurs.
- There is a risk of flooding in Tunnel 6, and there is currently no flood protection system in place. However, a rating of 6 has been assigned to this action since the owner deemed the probability and ultimate impact of a flood event to be noncritical.
- Installing new LED lights in Tunnel 1 would help the owner reduce maintenance even though the existing lights have a few years of service life left and are in relatively good condition. Lights are required in tunnels, so there is a regulatory requirement, but the existing lighting would also meet the requirement. Based on the risk assessment, it is assigned an RBU rating of 3.

Once a rating of 0 to 10 is assigned, the RBU score is calculated by multiplying the rating by 10 to achieve a score of between 0 and 100 (Table 5-9).

Table 5-9. Risk-based urgency score.

Preservation Action	Tunnel #	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
Ventilation upgrade to NFPA 502	1	1	25	96	2	Y	3	8	**80.0**
Install new LED lights	1	5	20	75	3	Y	1	3	**30.0**
CO system – repair to operating condition	2	2	20	90	4	Y	1	7	**70.0**
Repair active leak in ceiling	4	5	50	90	3	N	1	7	**70.0**
Remove existing concrete tunnel ceiling	6	0	50	100	3	N	1	10	**100.0**
Install flood gates	6	N/A	100	N/A	N/A	N	3	6	**60.0**

5.4.6 Calibrating the Risk-Based Urgency Score

There is considerable subjectivity in the determination of the RBU score. In addition, the scores are further aggregated by the multiplication factor of 10. Therefore, the AAMT's determination of the urgency might appear to have a significant impact on the final prioritization. The final RBU score is calculated based on the subjectively determined RBU rating assigned a value of between 0 and 10. As outlined previously, the RBU rating must be arrived at by considering the RBU criteria, including percent life expended, condition, regulatory compliance, and risk of unplanned events. Once the criteria have all been addressed, each preservation action's associated urgency can be evaluated using Table 5-8 to first consider the urgency as nonexistent (RBU rating of 0), low (RBU rating of 1 to 3), medium (RBU rating of 4 to 6), high (RBU rating of 7 to 9), or extreme (RBU rating of 10). Once categorized, the rating can be assigned at the bottom, middle, or top of the set range. As long as the preservation action is categorized with this method, the most the RBU rating can vary is two points. While this multiplies to 20 points in the RBU score, the RBU score is one of three scores used to determine the overall MOE score (Section 5.5). Still, to maintain the method's integrity, an agency assigning a high weight to the RBU score must carefully and methodically evaluate each preservation action using a systematic approach due to the subjective nature of this score. Accurate asset life and condition data are essential for appropriate consideration.

The example presented in Table 5-10 details the RBU rating assigned by a second reviewer at Agency X. The second reviewer considered all of the same information as the first reviewer (Table 5-9) and came up with some variations in RBU ratings.

Analysis of the second reviewer's choices:

- Ventilation upgrade to NFPA 502: Classified as high risk, the second reviewer chose to rate this action as a 9, feeling that the little remaining asset life and high probability of an unplanned event (fire) justified a higher rating than the 8 assigned by the first reviewer. The difference of 1 results in a 10% difference in RBU score and ultimately a 4.5-point difference when

Table 5-10. Risk-based urgency rating—second reviewer.

Preservation Action	Tunnel #	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) Reviewer 1	RBU Rating (1 to 10) Reviewer 2
Ventilation upgrade to NFPA 502	1	1	25	96	2	Y	3	8	9
Install new LED lights	1	5	20	75	3	Y	1	3	3
CO system – repair to operating condition	2	2	20	90	4	Y	1	7	9
Repair active leak in ceiling	4	5	50	90	3	N	1	7	8
Remove existing concrete tunnel ceiling	6	0	50	100	3	N	1	10	10
Install flood gates	6	N/A	100	N/A	N/A	N	3	6	6

considering the final measure of effectiveness score (Section 5.5; RBU score assigned a weight of 45% of total combined score).

- Install new LED lights: The second reviewer agreed with choosing the higher end of the low risk rating range and assigned the same rating as the first reviewer.
- CO system—repair to operating condition: Both reviewers categorized the CO system as a high risk. However, the second reviewer felt it should be rated at the top of the high-risk category, and the first reviewer assigned a rating at the bottom of the category. This rating difference of 2 results in a 20% difference in the RBU score and a 9-point difference in the RBU score component of the overall MOE.
- Repair active leak in ceiling: Classified as a high-risk item. Reviewer 1 felt that the repair should be rated at the bottom of the category, and Reviewer 2 rated it at the middle of the category, resulting in an RBU rating difference of 1 point.
- Remove existing concrete tunnel ceiling: The concrete tunnel ceiling is currently an extreme risk, and therefore both reviewers assigned an RBU rating of 10.
- Install flood gates: Overall, this action is classified as medium risk. However, due to the risk of Tunnel 6 flooding, both reviewers felt the top category rating of 6 should be assigned.

As discussed, while the assigned RBU ratings are subjective, using a logical process starting with the risk categories described, an AAMT can effectively develop the RBU score.

5.5 Measure of Effectiveness

The metric presented in this chapter uses an overall MOE as the indicator in establishing the priority of preservation actions to be implemented. 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 particular situation or 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 in consideration of its tunnels and overall agency goals and objectives. For the example provided in Table 5-11, the AAMT weighted the three scores as follows: agency LOS = 35%, cost-effectiveness = 20% and risk-based urgency = 45%.

Table 5-11. Measure of effectiveness score.

Levels of Service		Level of Service Score	Cost-Effectiveness Score	Risk-Based Urgency Score	MOE Score (Eq. 5-7)
Weights		35%	20%	45%	
Preservation Action	**Tunnel #**				
Ventilation upgrade to meet NFPA 502	1	66.0	1.9	80.0	**59.5**
Install new LED lights	1	78.0	2.4	30.0	**41.3**
CO system – repair to operating condition	2	63.2	100.0	70.0	**73.6**
Repair active leak in ceiling	4	89.0	100.0	70.0	**82.7**
Remove existing concrete tunnel ceiling	6	85.4	2.3	100.0	**75.4**
Install flood gates	6	66.0	2.8	60.0	**50.7**

Measure of effectiveness is computed as follows:

$$\text{MOE score} = W_{LOS} * \text{LOS} + W_{CE} * \text{CE} + W_{RBU} * \text{RBU} \qquad \text{Equation 5-7}$$

where

LOS = level-of-service score,
CE = cost-effectiveness score,
RBU = risk-based urgency score, and
W_{LOS}, W_{CE}, W_{RBU} = weights for the LOS, CE, and RBU, where $(W_{LOS} + W_{CE} + W_{RBU}) = 100$.

In Table 5-11, the highest MOE is for the repair of the active leak in the tunnel ceiling. This preservation action had relatively high values for all three scores, although the most heavily weighted RBU score was not the highest of the improvements being compared. The next highest scoring preservation action received the maximum RBU score, a significantly high impact on Agency X's LOS, but a low CE score. While the CO system repair received the maximum CE score, it ranked third in the list due to its moderate impact on the agency's LOS and lower RBU score. Observation of the data in this manner shows that the resulting MOE score is not easily predicted since the weighting performed in this final step affects the final outcome.

CHAPTER 6

Prioritization of Preservation Actions

6.1 Use of the Metric in Prioritization

The process outlined in Chapter 5 uses a simple metric that provides the basis for comparison of numerous alternatives to establish present and future priorities and for comparison of preservation actions in a single tunnel versus all tunnels in a certain region or over the entire tunnel system. The metric uses the combination of three scores into one MOE and allows each alternative activity to be weighted against the others and the priorities to be established. This process is represented visually in Appendix C: Highway Tunnel Preservation Prioritization Flowchart.

The methodology presented in Chapter 5 provides guidance to a tunnel owner for setting priorities. However, prioritization and programming for the next 5 or 10 years requires 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 available 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. There are many factors that go into an owner's ultimate decision on priorities, but the MOE methodology presented in Chapter 5 provides a first pass that can assist an owner in making these decisions.

Table 6-1 shows the priorities for each improvement based on the calculated MOE. The owner should review the prioritized list and then assign its own priorities to the list of projects. Ultimately, it is the user's prioritization that will be used in the funding and staffing analyses presented in Chapter 7.

For the selected preservation actions provided, the owner assigned new priorities in the user-defined priority column in Table 6-1. The owner chose to rate repairing the active leak in the ceiling, repairing the CO system, and upgrading the ventilation system as 1, 2, and 3, respectively, because of the agency's decision to focus on safety as described in Section 5.2.1 and because the ceiling removal is more costly and could be combined with installation of flood gates in the future. For the full list of Agency X's preservation actions and prioritization, refer to Appendix D.

6.2 Use of the Metric for Evaluation of Alternatives

Inherent in the metric is the ability to evaluate various alternatives for a specific tunnel preservation action. Similar to the process of prioritizing multiple preservation actions, the MOE score can be used when evaluating these alternatives. This type of analysis considers alternatives that are used to select a single preservation action. Examples of this include lighting replacement,

Table 6-1. Prioritization of preservation actions.

Levels of Service		LOS Score	Cost-Effectiveness Score	Risk-Based Urgency Score	Measure of Effectiveness Score	Calculated Priority	User-Defined Priority
Weights		35%	20%	45%	100%		
Preservation Action	Tunnel #						
Ventilation upgrade to meet NFPA 502	1	66.0	1.9	80.0	59.5	4	3
Install new LED lights	1	78.0	2.4	30.0	41.3	6	5
CO system – repair to operating condition	2	63.2	100.0	70.0	73.6	3	2
Repair active leak in ceiling	4	89.0	100.0	70.0	82.7	1	1
Remove existing concrete tunnel ceiling	6	85.4	2.3	100.0	75.4	2	4
Install flood gates	6	66.0	2.8	60.0	50.7	5	6

fire alarm upgrades, supervisory control and data acquisition (SCADA) systems, and different methods of wall repair. Two examples are presented in the following sections to highlight the use of the MOE in evaluating alternatives.

6.2.1 Lighting Replacement Comparison

Table 6-2 compares three lamp options for replacing the existing tunnel lighting system. High-pressure sodium (HPS), induction lighting, and LED fixtures are considered. Note that the no-build option is not included. The reason for this will be explained in the discussion of cost-effectiveness.

Since the table compares options for the same overall preservation action (i.e., replacing the lighting), the LOS scores will not vary much. The ratings, although subjective, are nearly the same for many of the categories, with minor variances. In this case, reliability, safety, and security are uniform across all three options as they are not affected by the light fixture chosen. However, the whiter light emanating from the induction and LED lamps may be perceived to provide better quality of service than the yellow tint of the HPS, as reflected in a higher rating. Also, the life expectancy of an LED lamp is longer than the others, and the lamps require less maintenance. Similarly, LED and induction lighting use less energy and are therefore more environmentally friendly if carbon footprint is compared.

The CE scores shown in Table 6-3 are the result of the differences between the various options. The initial cost to upgrade or replace the system, the annual energy savings, and the annual reduction in maintenance costs can vary significantly. The changes in annual energy and maintenance costs are compared to the existing system, which inherently considers the no-build option. Thus, it is not necessary to consider the no-build option as one of the alternatives as long as the costs are evaluated relative to the existing system.

Table 6-2. Level-of-service score for lighting replacement.

Levels of Service		Reliability	Safety	Security	Preservation	Quality of Service	Environment	LOS Score (Eq. 5-1)
Weights		20%	40%	5%	18%	15%	2%	
Preservation Action	Tunnel #							
Replace lighting system with HPS lamps	1	4	3	2	3	3	2	**62.6**
Replace lighting system with induction lamps	1	4	3	2	4	5	3	**72.6**
Replace lighting system with LED lamps	1	4	3	2	5	5	3	**76.2**

Since the comparison is of various lighting systems, the RBU score in Table 6-4 is the same for each. The remaining life of the existing lighting system, the original service life, and the existing condition are all the same and are not relevant to the fixture type chosen since these factors apply to the existing lighting system. If the required system, in this case the lighting, needs to be replaced or upgraded, then each alternative will have the same RBU score.

The MOE score in Table 6-5 combines the three scores from the previous example with alternative preservation actions. In this case, there is little variability in the LOS and CE scores and no variability in the RBU score. Therefore, the MOE scores are similar. Replacing the current lighting system with LED lights yields the highest LOS and CE scores and, therefore, the highest MOE score. The induction system lamps are prioritized second due to their greater impact on the LOS score, which the agency has placed greater weight on than the CE score.

Table 6-3. Cost-effectiveness score for lighting replacement.

Preservation Action	Tunnel #	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)
Replace lighting system with HPS lamps	1	3,090,000	123,600	–2,500	3,170,067	25	40	182,050	4.55	**2.2**
Replace lighting system with induction lamps	1	3,120,000	124,800	40,000	3,941,326	25	40	226,342	5.66	**1.8**
Replace lighting system with LED lamps	1	3,400,000	136,000	-68,500	2,516,893	20	40	169,175	4.23	**2.4**

Table 6-4. Risk-based urgency score for lighting replacement.

Preservation Action	Tunnel #	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
Replace lighting system with HPS lamps	1	5	20	75	1	N	1	3	**30.0**
Replace lighting system with induction lamps	1	5	20	75	1	N	1	3	**30.0**
Replace lighting system with LED lamps	1	5	20	75	1	N	1	3	**30.0**

While the use of the metric for lighting replacement alternatives compared three similar types of preservation actions, the metric can also be used to evaluate repairing or replacing tunnel systems or structural components, as highlighted in the example in the next section.

6.2.2 Ceiling Improvement—Repair Versus Replacement

The previous example compared the use of varying materials to accomplish one improvement in the tunnel—a lighting upgrade. An agency often has to decide whether to continue to maintain an existing asset, replace it, or eliminate it altogether if possible. It may be necessary to bundle two or more preservation actions when comparing them using the MOE since one action is predicated on another. In this example, the agency evaluates whether to repair an existing tunnel ceiling or remove it altogether. Because the tunnel ceiling cannot typically be removed without modification of the ventilation system, it might make more sense to evaluate a combination of ceiling and ventilation improvements in one preservation action to facilitate comparison. For the purpose of the example provided in this section, however, assume that the ceiling removal is independent of the ventilation improvement.

Table 6-6 shows that removal of the ceiling more closely achieves the goals of the agency than repairing the existing ceiling. While repairs may solve problems associated with deteriorated and

Table 6-5. Measure of effectiveness score and calculated priority for lighting replacement.

Levels of Service		LOS Score	Cost-Effectiveness Score	Risk-Based Urgency Score	Measure of Effectiveness Score	Calculated Priority
Weights		35%	20%	45%	100%	
Preservation Action	Tunnel #					
Replace lighting system with HPS lamps	1	62.6	2.2	30.0	35.8	3
Replace lighting system with induction lamps	1	72.6	1.8	30.0	39.3	2
Replace lighting system with LED lamps	1	76.2	2.4	30.0	40.6	1

Table 6-6. Level-of-service score for ceiling study.

Levels of Service		Reliability	Safety	Security	Preservation	Quality of Service	Environment	LOS Score (Eq. 5-1)
Weights		20%	40%	5%	18%	15%	2%	
Preservation Action	Tunnel #							
Repair ceiling	6	3	3	N/A	2	3	N/A	**52.2**
Remove ceiling	6	4	4	N/A	4	5	N/A	**77.4**

spalling concrete for a period of time, the agency has experienced situations where the repair eventually failed as well. These failures resulted in unsafe conditions and caused the agency to close the tunnel to make repairs. For these reasons, the owner assigned lower ratings to the repair option. Furthermore, the repair will likely require future maintenance and repair, whereas removal of the ceiling eliminates the problem entirely. Thus, a lower score for preservation was also assigned.

The cost-effectiveness of the two options, as shown in Table 6-7, is based on the LCC for each since the ADT value is the same for each option. In this case, the option to repair the ceiling is more cost-effective than the ceiling removal option due to the high initial cost of removal. Since the current condition of the ceiling warrants significant repairs, and these repairs would need to be repeated in future years, the ceiling repair option receives a moderately low CE score.

Because the RBU is based on the existing asset, in this case the existing ceiling, the RBU scores are the same for both alternatives (see Table 6-8).

Table 6-7. Cost-effectiveness score for ceiling study.

Preservation Action	Tunnel #	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)
Repair ceiling	6	140,000	5,600	12,000	454,357	50	75	17,659	0.24	**42.5**
Remove ceiling	6	8,000,000	800,000	–20,000	8,285,405	50	75	322,016	4.29	**2.3**

Table 6-8. Risk-based urgency score for ceiling study.

Preservation Action	Tunnel #	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
Repair ceiling	6	0	50	100	3	N	Low	10	**100**
Remove ceiling	6	0	50	100	3	N	Low	10	**100**

Table 6-9. Measure of effectiveness score and calculated priority for ceiling study.

Levels of Service		LOS Score	Cost-Effectiveness Score	Risk-Based Urgency Score	Measure of Effectiveness Score	Calculated Priority
Weights		35%	20%	45%	100%	
Preservation Action	Tunnel #					
Repair ceiling	6	52.2	42.5	100	71.8	2
Remove ceiling	6	77.4	2.3	100	72.6	1

Although the ceiling removal option receives a low CE score, Agency X weighted cost-effectiveness as only 20% due to its high priority on safety and emphasis on minimizing risk (see Table 6-9). Therefore, the ceiling removal option receives a higher MOE score due to its moderately high impact on the agency's LOS. The ceiling repair option will not solve the current issue in Tunnel 6 and will lead to additional costly repairs in the future. These repairs are not only a cost issue, they also affect the overall preservation of the tunnel, quality of service, safety, and the reliability of the tunnel's operation.

CHAPTER 7

Implementation of Preservation Actions

This guide offers a method for comparing and prioritizing tunnel preservation actions. Agencies have the option of following the prioritization plan produced by this method or modifying the plan based on other factors. 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 implementing 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.

Preservation actions are often implemented with limited funds and agency staff. The following sections discuss issues concerning funding and staffing for tunnel preservation action implementation as well as how funding and staffing needs can be calculated using the metric provided in Chapter 5.

7.1 Funding Scenarios

Traditionally, funding for the overall transportation infrastructure comes from various taxes, fees, and bonds, as described in the following and shown in Figure 7-1:

- Federal fuel tax: The federal fuel tax is an excise tax on gasoline and diesel fuel sold throughout the country.
- State fuel tax: Each state has its own fuel taxes. Some states base the tax on a percentage of the sales price, while others tie it to inflation or the Consumer Price Index.[19]
- Sales tax: According to the Tax Foundation, seven states (CA, CT, GA, IL, IN, MI, NY) collect sales tax on gasoline purchases.[20]
- Tolls: Tolls are collected by different organizations. Some special roadways (e.g., turnpikes), bridges, and tunnels are tolled for revenue. It should be noted that the Massachusetts Department of Transportation has a funding stream dedicated solely to tunnels; tolls collected at Boston tunnels are set aside specifically for the operation and maintenance of tunnels.
- Bonds: Some state and local governments issue bonds to finance transportation needs, where the government agency sells bonds to investors and then repays the borrowed money, plus interest, over a predetermined amount of time. Often, bonds are used to finance large construction projects.
- General fund: Some states appropriate money from the general fund to fund the transportation infrastructure. Income taxes, sales taxes, property taxes, and other fees all contribute to state general funds.

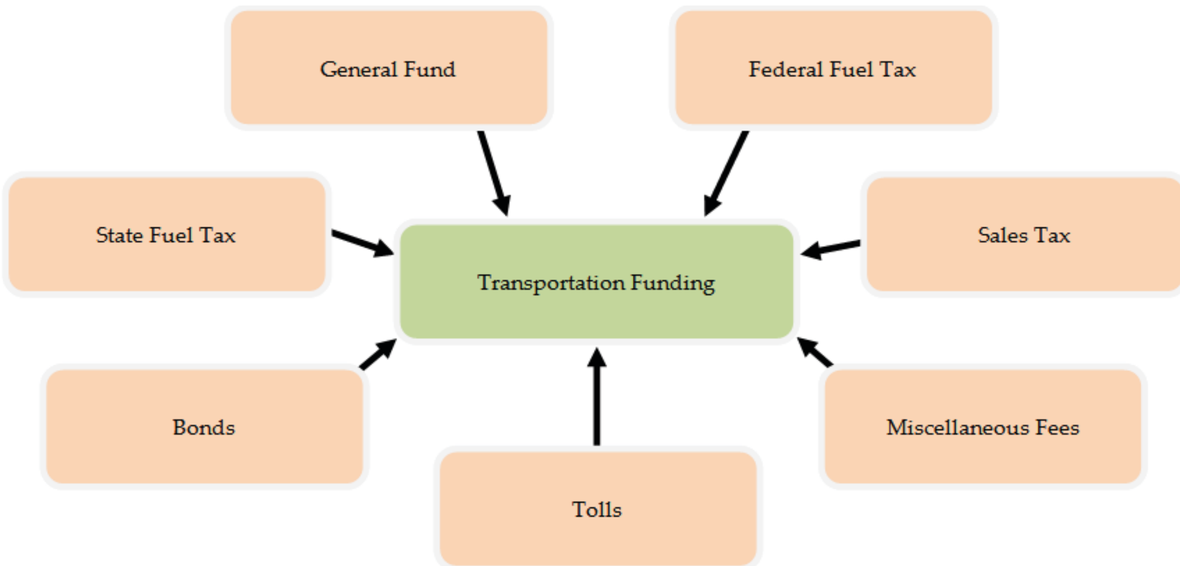


Figure 7-1. Highway tunnel preservation funding sources.

- Miscellaneous fees: Miscellaneous fees include funds from vehicle registration fees, driver's license renewal fees, and other sources.[19]

To adequately maintain its tunnels in good condition, the tunnel agency must identify the preservation actions needed and must obtain the funding to accomplish these actions. The capital planning process is achieved through either a top-down or a bottom-up funding approach, or a combination of both, as described in Sections 7.1.1 and 7.1.2.

7.1.1 Top-Down Funding

As shown in Figure 7-1, transportation infrastructure is funded through gas tax revenues at the federal and state levels, tolls, bonds, sales taxes, the general fund, and miscellaneous fees (licenses, registrations, etc.). From the total funds anticipated for each year, the state government creates a transportation budget with a portion of that budget allocated for operation and maintenance of the agency's tunnels. For toll agencies, funding for tunnels may come entirely from tolls or a combination of tolls, bonds, and (sometimes) federal dollars.

Most highway tunnel owners in the United States are departments of transportation or authorities who own considerably more assets than just tunnels. Bridges, highways, and facilities require a significant portion of the annual revenue to maintain them in a safe, reliable condition; tunnel improvements often compete for this revenue. Funding must be allocated by upper management to the various transportation needs; it is critical that a proportionate amount of funds be allocated to tunnels to maintain them as part of the overall transportation system.

In a top-down approach, the budget for tunnel preservation is established based on a formula percentage of the overall transportation funding. Once this budget has been set, the agency evaluates the priorities and selects the improvements to be implemented for that year.

The example for Agency X is shown in Table 7-1. Agency X has determined it has a budget for tunnel improvements in Year 1 of $7 million, Year 2 of $10 million, and Year 3 of $13 million. Based on the initial user-defined prioritization, the leak repair, CO system repair, and ventilation upgrade will fit within the budget cap for Year 1, totaling $6.3 million. However, with the remaining funds the agency elects to include a few low-cost improvements as well. It adjusts its user

Table 7-1. Top-down funding.

Preservation Action	Tunnel #	Initial Cost ($)	Agency Oversight Cost ($)	Total Cost ($)	User-Defined Priority	Cumulative Annual Cost ($)	Year Implemented
Repair active leak in ceiling	4	10,000	1,000	11,000	1	11,000	1
CO system – repair to operating condition	2	32,000	3,200	35,200	2	46,200	1
Ventilation upgrade to meet NFPA 502	1	5,700,000	570,000	6,270,000	3	6,316,200	1
Remove existing concrete tunnel ceiling	6	8,000,000	800,000	8,800,000	4	9,064,000	2
Install new LED lights	1	3,400,000	340,000	3,740,000	5	3,967,766	3
Install flood gates	6	8,000,000	320,000	8,320,000	6	12,794,454	3

priority accordingly. In Year 2, if it stays with the original prioritization, it can accomplish the removal of the ceiling within the available budget, and it can also include a few minor upgrades with the remaining funding. Similarly, for Year 3, LED lights and flood gates will be installed, in addition to a minor upgrade. As observed in this example, using the top-down method allows low-cost options to achieve higher priority in order to fully utilize available funding.

7.1.2 Bottom-Up Funding

In order for transportation agencies to fully understand their needs in development of their capital plans, a bottom-up approach to defining the needs is important. For the entire transportation system, this could include how many vehicles to replace, how much salt is required to purchase for cold weather climates, how much resurfacing is required to meet International Roughness Index (IRI) goals for pavement smoothness, and how many bridges are planned for rehabilitation or replacement due to condition. For those owners with tunnels, it would include an assessment of element and system conditions or anticipated preservation actions from planned code upgrades and the monies needed for these elements/systems to be preserved for future years.

For identified tunnel preservation actions, initial costs and LCC analyses should be performed, and then the improvements should be prioritized following the asset management method presented in this guide. The prioritized action plan can be incorporated into the agency's capital plans, and the associated costs will help set the agency's projected capital expenditures for several years. Based on the example shown in Table 7-1, the capital budget needed for Year 1 is $6,316,200, the budget required for Year 2 is $9,064,000, and for Year 3 it is $12,794,454. These estimates include escalation but will need to be increased to account for other project costs, such as agency costs, that have not been included.

Figure 7-2 presents a flowchart detailing how top-down funding and bottom-up needs determinations come together in this funding process.

Ideally, the available funding would be sufficient to implement all needed preservation actions, but that is rarely, if ever, the case. Agencies must continually face constrained funding environments.

Figure 7-2. Highway tunnel preservation funding flowchart.

7.1.3 Communicating the Need

In order to minimize the gap between funding and needs, the funding gap must be communicated, first within the agency and then to various government officials, to formulate and implement strategies for both maintenance and asset preservation. Furthermore, the need must be communicated in such a way that each party understands the issue. The metric presented in this guide provides agencies the supporting backup needed to communicate the impact of funding on agency goals and desired performance. When a comprehensive communication program is required, the agency should consider using *NCHRP Report 742: Communicating the Value of Preservation: A Playbook*[21] as a guide to establishing such a program. The playbook is written as a guide that agency staff can use in formulating an effective strategy for communicating the importance of highway maintenance and preservation, applying criteria and methods for evaluating the effectiveness of a communication strategy, and adjusting a strategy, if necessary, to ensure its effectiveness. Applying the methods and examples presented in the playbook can help an agency's stakeholders, including the general public, elected officials, and senior agency managers, to understand the scope, scale, and urgency of their highway system's preservation and maintenance needs.

The metric included in this guide also facilitates communication by capturing and presenting costs for preservation actions tied to specific performance goals. Each preservation action earns a score for level of service, cost-effectiveness, and risk-based urgency. By sorting the results of the analysis, it is possible to report the funding needed for projects that will improve safety, reduce environmental impacts, or mitigate high-risk events. As an example, Agency X would like to report the anticipated costs for improvements that would significantly affect safety. Significant safety improvements would have received a 4 or 5 for the LOS rating. Table 5-4 shows that all of the listed improvements were assigned a 4 or 5 for safety, and therefore all of the costs shown in Table 7-2 improve safety. If the environmental improvements were desired, Table 5-4 shows that only one preservation action significantly affected the environment—the addition of LED lighting. Therefore, the cost of the LED lighting improvement would be communicated as the funding needed for environmental improvements. The data provided in these tables can be easily sorted in many ways to explain the funding needed to make a specific impact.

Another example to determine the funding needed to achieve a particular performance goal uses the condition state that is included in the RBU evaluation. If the agency performance measure is to maintain a condition state of CS2 or higher for its tunnels, the data can be sorted to identify all preservation actions that apply to CS3 or CS4. The funding required to improve these assets would be the total project costs associated with those preservation actions. Additional, similar evaluations can be made to determine funding needed to meet other performance goals but may require the addition of fields to identify which preservation actions affect the specific performance goals.

7.2 Staffing

Tunnel owners maintain a certain level of effort to support agency requirements and their tunnel preservation programs. The tunnel preservation program includes preventive maintenance activities and rehabilitation (see Figure 7-3). Preventive maintenance is further categorized as cyclical (non-condition-based) and condition-based activities, as discussed in Chapter 4.

7.2.1 Staffing for Tunnel Operation, Maintenance, and Preservation

Organizationally, many tunnel owners include their tunnel programs as a subset of their overall bridge program and use the same personnel to perform maintenance and operational needs for both types of structures. Therefore, these agencies will not have dedicated tunnel personnel for maintenance but must share them between the various assets.

Some tunnel owners have dedicated staff for maintenance specifically for tunnels, whether on a state-wide, regional, or tunnel-specific basis. These staffing levels are driven by maintenance needs. Staffing levels may be adjusted from time to time due to the agency's overall commitment to achieve a specific staff level. In general, staffing levels usually remain constant from year to year, unless a reduction is enforced for that year or major improvements warrant the addition of staff for the duration of the work.

Most agencies, with or without a dedicated tunnel staff, perform some sort of tunnel maintenance in-house. Much of the time, it is basic preventive and cyclical preventive maintenance. When maintenance actions become more complex or when personnel become limited, maintenance is normally outsourced. When maintenance operations require tunnel closures, owners often augment in-house staff with outside contractors to expedite as much work as possible during

Table 7-2. Cost aggregation.

User-Defined Priority	Preservation Action	Tunnel #	Capital Cost ($)	% Labor (0 to 100)	Labor Cost ($)	% Agency Labor (0 to 100)	Agency Labor Cost ($)	Agency Oversight Cost ($)	Total Agency Labor Cost ($)	Total Labor Cost with Agency Oversight ($)	Materials Cost ($)	Subtotal Cost ($)	Funding Year (1+)	Escalation ($)	Total Cost ($)
1	Repair active leak in ceiling	4	10,000	50	5,000	0	0	1,000	1,000	6,000	5,000	11,000	1	0	11,000
2	CO system – repair to operating condition	2	32,000	80	25,600	0	0	3,200	3,200	28,800	6,400	35,200	1	0	35,200
3	Ventilation upgrade to meet NFPA 502	1	5,700,000	20	1,140,000	0	0	570,000	570,000	1,710,000	4,560,000	6,270,000	1	0	6,270,000
4	Remove existing concrete tunnel ceiling	6	8,000,000	65	5,200,000	0	0	800,000	800,000	6,000,000	2,800,000	8,800,000	2	264,000	9,064,000
5	Install new LED lights	1	3,400,000	30	1,020,000	0	0	340,000	340,000	1,360,000	2,380,000	3,740,000	3	227,766	3,967,766
6	Install flood gates	6	8,000,000	50	4,000,000	100	4,000,000	320,000	4,320,000	4,320,000	4,000,000	8,320,000	3	506,688	8,826,688

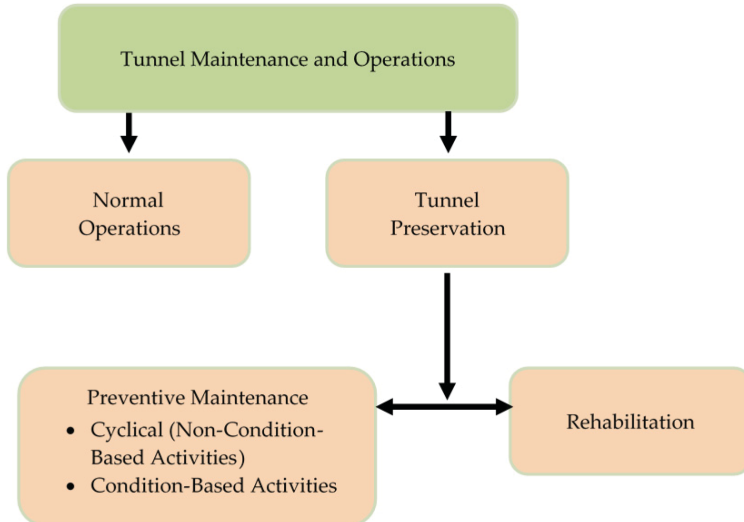


Figure 7-3. Highway tunnel maintenance and operations.

the closure period. Some agencies, like the District of Columbia Department of Transportation, outsource all maintenance to contractors using performance-based contracts.

Whether the maintenance work is performed in-house or is outsourced, tunnel owners should recognize the functions that must be performed by personnel. The next section reviews some of the most common staff functions.

7.2.2 Tunnel Staff Functional Duties

Tunnel owners should consider an organizational structure with some or all of the following personnel to meet the planning, operational, maintenance, and preservation needs of their tunnel(s). These personnel are identified in the 2015 FHWA TOMIE Manual as:

- Tunnel manager,
- Tunnel supervisor,
- Tunnel operators,
- Tunnel foreman,
- Tunnel mechanical specialist,
- Tunnel electrical specialist,
- Tunnel electronics/ITS specialist,
- Tunnel fire protection specialist,
- Tunnel safety/security specialist, and
- Tunnel laborer.

In addition, the program manager is defined by the NTIS. The functional duties of the key personnel to maintain an owner's tunnels can be described as follows:

- **Program manager:** The program manager is the individual in charge of tunnels, including the inspection program, and is responsible for tunnel inspection, reporting, and inventory. The program manager provides overall leadership and guidance to inspection team leaders. This individual, for certain agencies, may have other responsibilities, but is assigned as the program manager for that agency's tunnels.
- **Tunnel manager:** This person manages the tunnel facility and is generally responsible for establishing an effective operating program for the tunnel 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 of the tunnel facility personnel.

- **Tunnel supervisor:** This individual is in charge of the overall day-to-day operation and maintenance activities conducted at the tunnel facility; this person generates work assignments; issues work orders; schedules repairs and maintenance; orders spare parts and miscellaneous equipment; manages traffic and lane closures; responds to incidents, events, and accidents; maintains performance levels of the tunnel; approves the work of contractors and consultants; and communicates problems to the tunnel manager and facility engineer.
- **Tunnel operators:** These individuals monitor conditions related to traffic within the tunnel, including traffic flow rate, congestion, and accidents; the height of approaching trucks; variable message displays and output from control signals; concentrations of particulates, air flow, and fan performance; electric supply and power consumption; lighting intensity; weather conditions; and water accumulation and pump operation. These individuals also engage functional systems and coordinate emergency response to incidents within the tunnel.
- **Tunnel forepersons:** Forepersons lead a small team of discipline-specific specialists and general laborers; the foreperson is generally 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 years of relevant experience. Forepersons are typically 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 generally 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, and replacing belts. This specialist works with different types of mechanical equipment, including 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 for mechanical repairs.
- **Tunnel electrical specialists:** The electrical specialist generally 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, CCTV cameras, and so forth as appropriate for the tunnel facility. The electrical specialist should also be able to diagnose routine electrical problems and fully implement the designated quality measures for electrical repairs.
- **Tunnel electronics specialists:** The electronics specialist generally 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 supports equipment and systems such as power switchgears and panel boards with amp meters; power meters and frequency meters; environmental control systems; programmable logic controllers and monitoring systems; fire alarm systems; heating, ventilation, and air-conditioning (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 for the repair of electronic components.
- **Safety officers:** Safety officers coordinate emergency response with local fire departments, medical transport units, police, and so forth. These officers generally 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. The safety officers conduct drills and training for emergency preparedness. These officers also serve as liaisons between the tunnel facility and emergency response units such as firefighters, ambulances, medical evacuation (medivac) units, and hospitals.

- **Security officers:** Security officers respond to emergency situations, support emergency operations, patrol the facility, implement weather advisories, escort hazardous vehicles, inspect cargo, and so forth. Security officers participate in the development of response strategies for various tunnel-specific threat scenarios. These officers generally have experience in a police or tactical unit with specialized training in tunnel security. Security officers generally have patrol vehicles and towing equipment on site. These officers serve as liaisons between various police departments and the tunnel facility.
- **Tunnel laborers:** Laborers serve as versatile workers that perform an important multitude of 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 (mechanical, electrical, electronic) by moving heavy objects, cleaning equipment, tightening bolts, and so forth. Laborers facilitate tunnel operations by directing traffic, placing barricades, clearing debris, shoveling snow, removing disabled vehicles, and so forth.

7.2.3 Tunnel Staffing for Emergency Events

Emergency events, such as vehicular accidents damaging the tunnel structure, fire events causing structural and system damage, and failure of tunnel systems, may necessitate tunnel closure. Tunnel owners will most likely have in-house staff on site, or at a regional location, that can respond immediately to the event and call first responders, as needed. The tunnel agency may engage outside consultants or specialty contractors to evaluate conditions, assess damage, and render recommendations for reopening the tunnel.

7.2.4 Estimating Staffing Needs

The number of assigned staff will vary by tunnel owner, by how many tunnels the owner has, and by regional organizations when multiple tunnels are geographically spread throughout a state. Staffing is also dependent on whether the agency prefers and has the resources to perform maintenance and operations in-house or contracts the work to an outside company. An agency that performs much of the maintenance work in-house needs highly skilled staff, which requires advanced training, especially for systems that are electronic.

The number of staff can be estimated using the data collected to this point, but the costs need to be further aggregated to determine the labor that the agency will expend. Table 7-2 shows how the agency labor costs can be determined. Initially, the cost of project labor versus project materials is estimated. In the absence of more detailed cost information, labor cost can be approximated as a percent of the overall capital cost. At this point, agency oversight costs must be considered. If the agency is self-performing much of the work, the oversight costs may be minimal (e.g., 5% or less of the total project cost or, as a minimum, of the estimated labor costs). If the work is contracted out, an additional 10% would be more appropriate for agency oversight. For a rough estimation of agency labor cost, in the absence of a more detailed calculation, the AAMT should estimate what percent of the total labor cost will be agency labor versus labor of contracted personnel. The estimated percent is then multiplied by the project labor cost to obtain an estimation of agency labor cost. The number of staff needed to complete the preservation

Table 7-3. Agency staffing.

User-Defined Priority	Preservation Action	Tunnel #	Total Agency Labor Cost ($)	Agency Average Labor Rate ($/hr)	Agency Man-Hours	Cumulative Annual Agency Man-Hours	# Full-Time Staff Required	Cumulative # Full-Time Staff Required	Year Implemented
1	Repair active leak in ceiling	4	1,000	100	10	10	0.01	0.01	1
2	CO system – repair to operating condition	2	3,200	100	32	42	0.02	0.02	1
3	Ventilation upgrade to meet NFPA 502	1	570,000	100	5,700	5,742	2.7	2.8	1
4	Remove existing concrete tunnel ceiling	6	800,000	100	8,000	8,000	3.8	3.8	2
5	Install new LED lights	1	340,000	100	3,400	3,400	1.6	1.6	3
6	Install flood gates	6	4,320,000	100	43,200	46,600	20.8	22.4	3

action can be computed by dividing the agency labor cost by an average hourly rate considering the staff that would be associated with that work. Agency staffing is provided in Table 7-3.

In the examples in Table 7-2, most of the work requires specialized contractors, so the agency will contract out for each of the tasks, with the exception of the flood gate installation. The agency intends to complete this work itself, and therefore the hours to complete are estimated using an average staff rate.

If the preservation action is to be implemented in the current year, enter 1 in the funding year column to negate escalation.

Once the total staff hours are known for each preservation action, the total number of staff to complete the work can be calculated. The calculation for the number of staff shown in Table 7-3 assumes a 1-year duration for each of the preservation actions.

7.2.5 Computerized Maintenance Management Systems (CMMSs)

Some tunnel owners use CMMSs to create, track, and complete work orders for tunnel maintenance. These software systems often provide means to track the time required to complete maintenance procedures, and this information can be helpful in estimating staffing needs for an agency. CMMSs not only provide projected hourly timelines for performing maintenance functions but also create a searchable history of maintenance events and recorded notes by staff.

Abbreviations and Acronyms

AAMT	Agency Asset Management Team
ACDV	Annual Cost per Daily Vehicle
ADT	Average Daily Traffic
ALCC	Annual Life-Cycle Cost
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CCTV	Closed-Circuit Television
CE	Cost-Effectiveness
CMMS	Computerized Maintenance Management System
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPVC	Corrugated Polyvinyl Chloride
CS	Condition State
DC	Direct Current
ERP	Emergency Response Plan
FM	Frequency Modulation
HMI	Human–Machine Interface
HPS	High-Pressure Sodium
HVAC	Heating, Ventilation, and Air Conditioning
i	Discount Rate
I	Inflation
IRI	International Roughness Index
ITS	Intelligent Transportation Systems
kVA	Kilovolt Amperes
LCC	Life-Cycle Cost
LE	Life Expended
LED	Light-Emitting Diode
LOS	Level of Service
LRFD	Load and Resistance Factor Design
MAP-21	Moving Ahead for Progress in the 21st Century Act
MOE	Measure of Effectiveness
N/A	Not Applicable
NEMA	National Electric Manufacturers Association
NFPA	National Fire Protection Association
NTIS	National Tunnel Inspection Standards
PA	Preservation Action
PMT	Page term: A function in Excel that returns the payment amount for a loan based on an interest rate and a constant payment schedule
Psi	Pounds per Square Inch

PV	Present Value
RBU	Risk-Based Urgency
RR	Rate of Return
SEM	Sequential Excavation Method
SMARTER	Specific, Measurable, Achievable, Relevant, Time-Bound, Evaluation, Reassess
TBM	Tunnel Boring Machine
TOMIE	*Tunnel Operations, Maintenance, Inspection, and Evaluation Manual*
VFD	Variable Frequency Drive

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APPENDIX A

Description of Tunnel Types and Systems

A.1 Tunnel Types

This section describes the various types of highway tunnels. These tunnel types are described by their shape, liner type, invert type, construction method, and tunnel finishes. It should be noted that other types may exist currently or be constructed in the future as new technologies become available. The purpose of this section is to look at the types that are most commonly used in tunnel construction to help the inspector properly classify any given tunnel. As a general guideline, a minimum length of 100 m (~300 ft) was used in defining a tunnel for inventory purposes. This length is used primarily to exclude long underpasses; however, other reasons for using the tunnel classification may exist, such as the presence of lighting or a ventilation system, which could override the length limitation.

A.1.1 Shapes

As shown in Figures A-1 to A-4, there are four main shapes of highway tunnels: circular, rectangular, horseshoe, and oval/egg. The different shapes typically relate to the method of construction and the ground conditions in which they were constructed. Although many tunnels will appear rectangular from inside, due to horizontal roadways and ceiling slabs, the outside shape of the tunnel defines its type. Some tunnels may be constructed using combinations of these types due to different soil conditions along the length of the tunnel. Another possible highway tunnel shape that is not shown is a single box with bidirectional traffic.

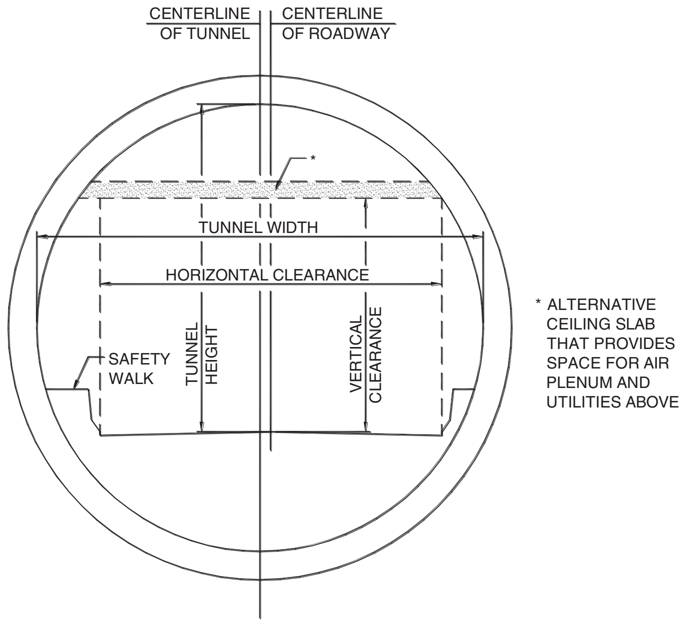
A.1.2. Liner Types

Tunnel liner types can be described using the classifications of:

- Unlined rock or rock lining,
- Rock reinforcement systems,
- Shotcrete,
- Ribbed systems,
- Segmental linings,
- Placed concrete, and
- Slurry walls.

Unlined Rock or Rock Lining

As the name suggests, an unlined rock tunnel is one in which no lining exists. Linings of other types may exist at portals or at limited zones of weak rock. This type of liner was common in older railroad tunnels in the western mountains, some of which have been converted into highway tunnels for local access.

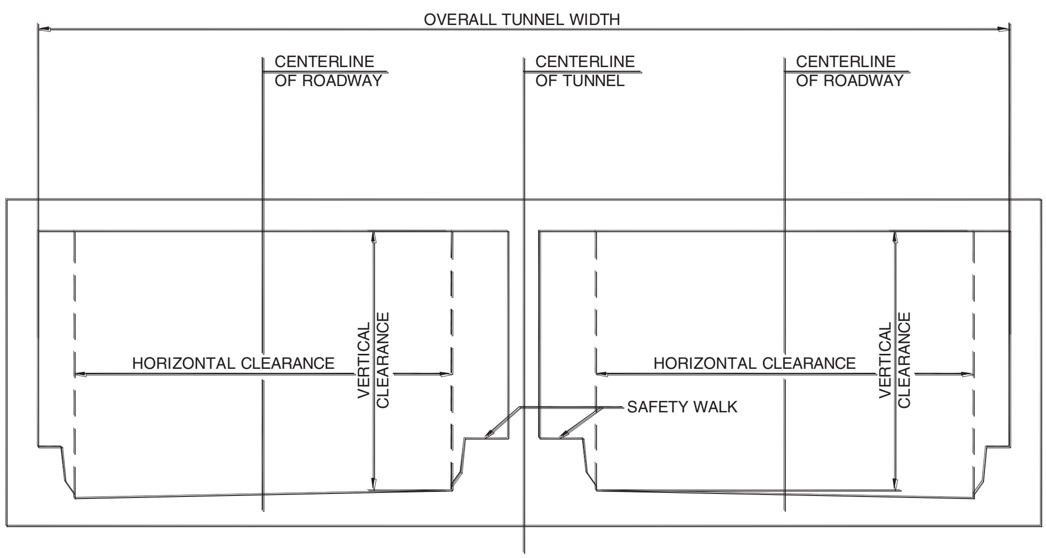


Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-1. Circular tunnel with two traffic lanes and one safety walk.

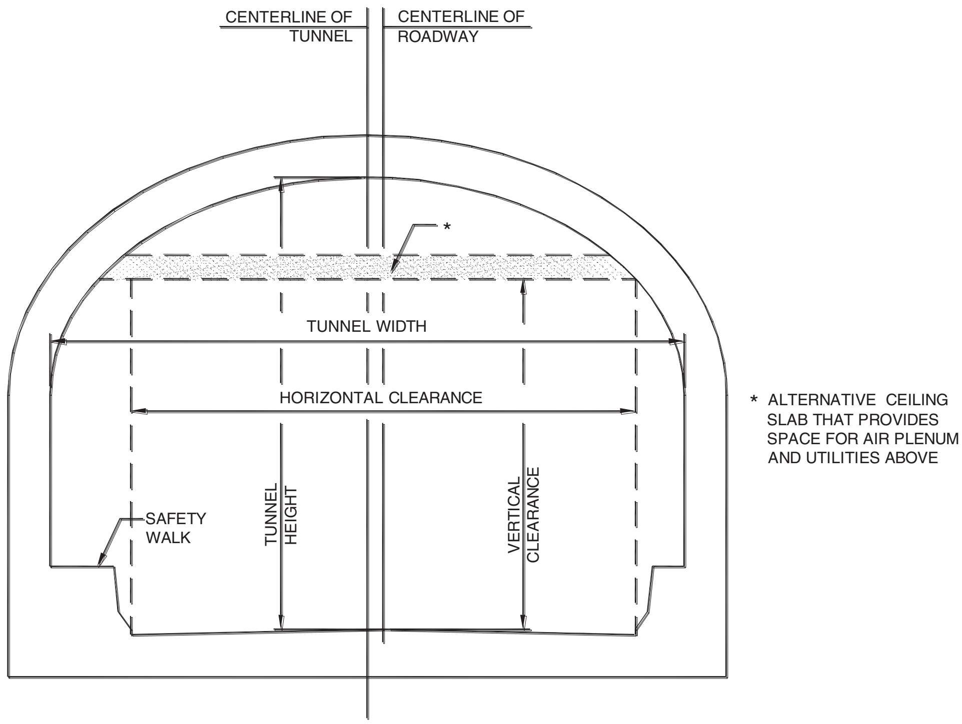
Rock Reinforcement Systems

Rock reinforcement systems are used to add additional stability to rock tunnels in which structural defects exist in the rock. The intent of these systems is to unify the rock pieces to produce a composite resistance to the outside forces. Reinforcement systems include the use of metal straps and mine ties with short bolts, untensioned steel dowels, or tensioned steel bolts. To prevent small fragments of rock from spalling off the lining, wire mesh, shotcrete, or a thin concrete lining may be used in conjunction with these systems.



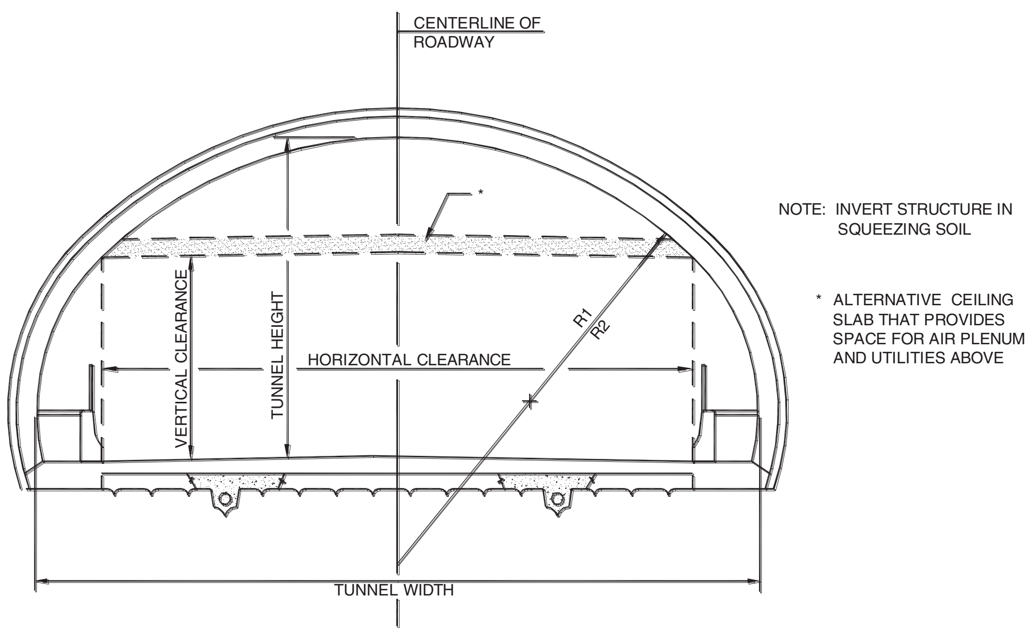
Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-2. Rectangular, double-box tunnel with two traffic lanes and one safety walk in each box.



Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-3. Horseshoe tunnel with two traffic lanes and one safety walk.



Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-4. Oval/egg tunnel with three traffic lanes and two safety walks.

Shotcrete

Shotcrete is appealing as a lining type due to its ease of application and short stand-up time. Shotcrete is primarily used as a temporary application prior to a final liner being installed or as a local solution to instabilities in a rock tunnel. However, shotcrete can be used as a final lining. When this is the case, it is typically placed in layers and can have metal or randomly oriented synthetic fibers as reinforcement. The inside surface can be finished smooth as with regular concrete; therefore, it is difficult to determine the lining type without having knowledge of the construction method.

Ribbed Systems

Ribbed systems are typically two-pass systems for lining a drill-and-blast rock tunnel. The first pass consists of timber, steel, or precast concrete ribs, usually with blocking between them. This provides structural stability to the tunnel. The second pass typically consists of poured concrete that is placed inside of the ribs. Another application of this system is to form the ribs using prefabricated reinforcing bar cages embedded in multiple layers of shotcrete. One other soft-ground application is to place barrel-stave timber lagging between the ribs.

Segmental Linings

Segmental linings are primarily used in conjunction with a tunnel boring machine (TBM) in soft ground conditions. The prefabricated lining segments are erected within the cylindrical tail shield of the TBM. These prefabricated segments can be made of steel, concrete, or cast iron and are usually bolted together to compress gaskets for preventing water penetration.

Placed Concrete

Placed concrete linings are usually the final linings that are installed over any of the previous initial stabilization methods. They can be used as a thin cover layer over the primary liner to provide a finished surface within the tunnel or to sandwich a waterproofing membrane. They can be reinforced or unreinforced. They can be designed as a nonstructural finish element or as the main structural support for the tunnel.

Slurry Walls

Slurry wall construction types vary but typically are made by excavating a trench that matches the proposed wall profile. This trench is continually kept full with a drilling fluid during excavation, which stabilizes the sidewalls. A reinforcing cage is then lowered into the slurry, or soldier piles are driven at a predetermined interval, and finally, tremie concrete is placed into the excavation, which displaces the drilling fluid. This procedure is repeated in specified panel lengths, which are separated with watertight joints.

A.1.3 Invert Types

The invert of a tunnel is the slab on which the roadway is supported. There are two main methods for supporting the roadway; one is by placing the roadway directly on-grade at the bottom of the tunnel structure, and the other is to span the roadway between sidewalls to provide space under the roadway for ventilation and utilities. The first method is also employed in many highway tunnels over land where ventilation is supplied from above the roadway level.

The second method is commonly found in circular highway tunnels that must provide a horizontal roadway surface wide enough for at least two lanes of traffic; therefore, the roadway slab is suspended off the tunnel bottom at a particular distance. The void is then used for a ventilation plenum and other utilities. The roadway slabs in many of the older highway tunnels in New York

City are supported by placing structural steel beams encased in concrete that span transversely to the tunnel length and are spaced between 750 mm (30 in.) and 1,500 mm (60 in.) on centers. Newer tunnels, similar to the second Hampton Roads Tunnel in Virginia, provide structural reinforced concrete slabs that span the required distance between supports.

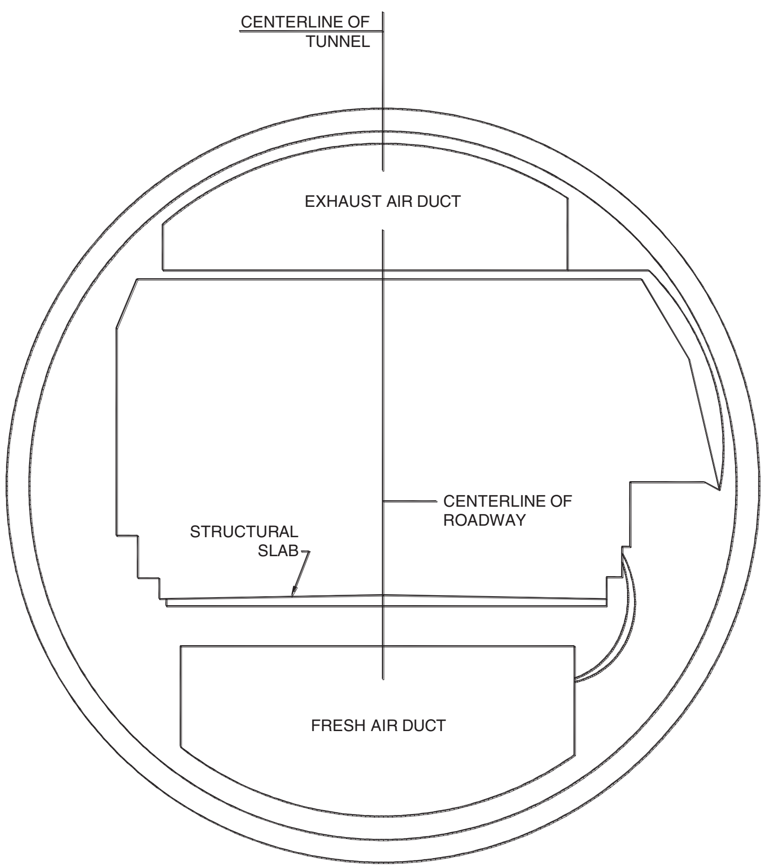
It is necessary to determine the type of roadway slab used in a given tunnel because a more extensive inspection is required for a structural slab than for a slab on grade. Examples of structural slabs in common tunnel shapes are shown in Figures A-5 to A-7.

A.1.4 Construction Methods

As mentioned previously, the shape of the tunnel is largely dependent on the method used to construct the tunnel. Table A-1 lists the six main methods used for tunnel construction with the shape that typically results. Brief descriptions of the construction methods follow.

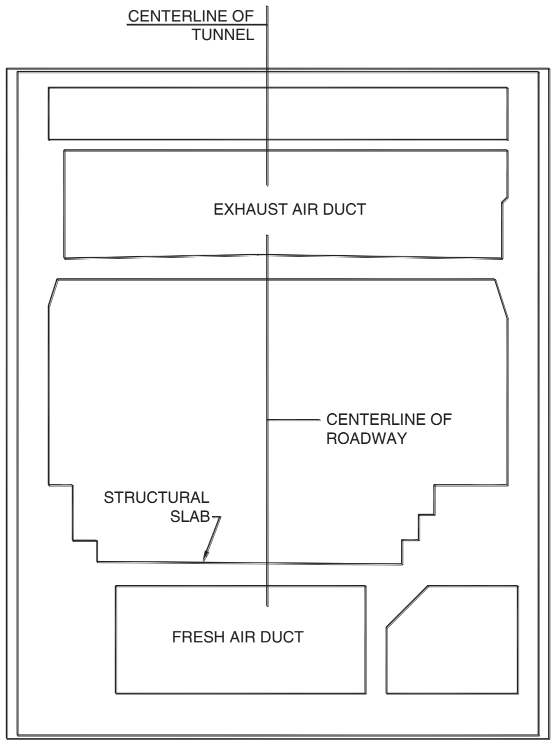
Cut and Cover

This method involves excavating an open trench in which the tunnel is constructed to the design finish elevation and subsequently covered with various compacted earthen materials and soils. Certain variations of this method include using piles and lagging, tie-back anchors, or slurry wall systems to construct the walls of a cut-and-cover tunnel.



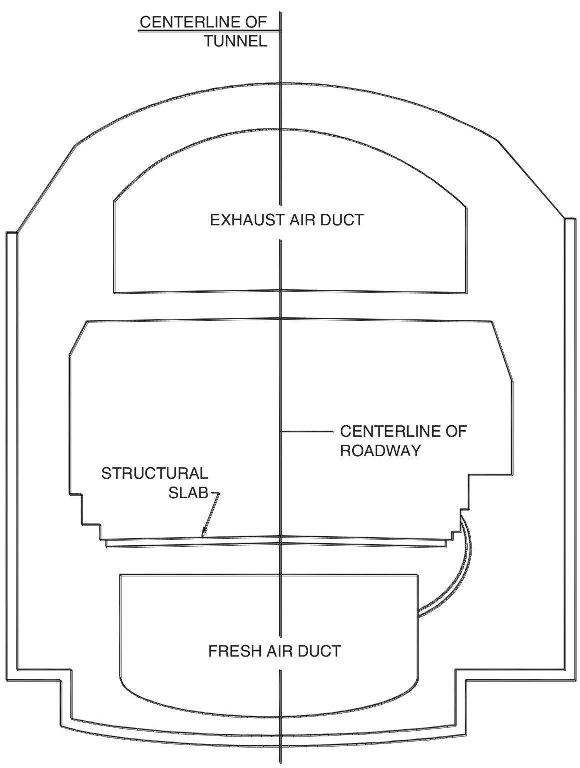
Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-5. Circular tunnel with a structural slab that provides space for an air plenum below.



Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-6. Single-box tunnel with a structural slab that provides space for an air plenum below.



Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-7. Horseshoe tunnel with a structural slab and an air plenum below.

Table A-1. Construction methods.

	Circular	Horseshoe	Rectangular
Cut and cover			X
Shield driven	X		
Bored	X		
Drill and blast	X	X	
Immersed tube	X		X
Sequential excavation		X	
Jacked tunnels	X		X

Shield Driven

This method involves pushing a shield into the soft ground ahead. The material inside the shield is removed, and a lining system is constructed before the shield is advanced further.

Bored

This method refers to using a mechanical TBM in which the full face of the tunnel cross-section is excavated at one time using a variety of cutting tools that depend on ground conditions (soft ground or rock). The TBM is designed to support the adjacent soil until temporary (and subsequently permanent) linings are installed.

Drill and Blast

An alternative to using a TBM in rock situations is to manually drill and blast the rock and remove it using conventional conveyor techniques. This method was commonly used for older tunnels and is still used when it is determined cost-effective or in difficult ground conditions.

Immersed Tube

When a canal, channel, river, or so forth needs to be crossed, this method is often used. A trench is dug at the water bottom, and prefabricated tunnel segments are made watertight and sunken into position, where they are connected to the other segments. Afterward, the trench may be backfilled with earth to cover and protect the tunnel from the waterborne traffic (e.g., ships, barges, and boats).

Sequential Excavation

Soil in certain tunnels may have sufficient strength such that excavation of the soil face by equipment in small increments is possible without direct support. This excavation method is called the sequential excavation method. Once excavated, the soil face is then supported using shotcrete, and the excavation is continued for the next segment. The cohesion of the rock or soil can be increased by injecting grouts into the ground prior to excavation of that segment.

Jacked Tunnels

The method of jacking a large tunnel underneath certain obstructions (highways, buildings, etc.) that prohibit the use of typical cut-and-cover techniques for shallow tunnels has been used successfully in recent years. This method is considered when the obstruction cannot be moved or temporarily disturbed. First, jacking pits are constructed. Then, tunnel sections are constructed in the jacking pit and forced by large hydraulic jacks into the soft ground, which is systematically removed in front of the encroaching tunnel section. Sometimes if the soil above the proposed tunnel is poor, it is stabilized through various means such as grouting or freezing.

A.1.5 Tunnel Finishes

The interior finish of a tunnel is important to the overall tunnel function. The finishes must meet the following standards to ensure tunnel safety and ease of maintenance. Tunnel finishes must be:

- Designed to enhance tunnel lighting and visibility,
- Fire resistant,
- Precluded from producing toxic fumes during a fire,
- Able to attenuate noise, and
- Easy to clean.

A brief description of the typical types of tunnel finishes that exist in highway tunnels is given in the following.

Ceramic Tile

This type of tunnel finish is the most widely used by tunnel owners. Tunnels with a concrete or shotcrete inner lining are conducive to tile placement because of their smooth surfaces. Ceramic tiles are extremely fire resistant, economical, easily cleaned, and good reflectors of light due to the smooth, glazed exterior finish. They are not, however, good sound attenuators. In new tunnels, this has been addressed via other means. Typically, tiles are 106 mm (4 ¼ in.) square and can be ordered in any color desired. They differ from conventional ceramic tile in that they require a more secure connection to the tunnel lining to prevent the tiles from falling onto the roadway below. Even with a more secure connection, tiles may need to be replaced eventually because of normal deterioration. Additional tiles are typically purchased at the time of original construction since they are specifically made for that tunnel. The additional amount purchased can be up to 10% of the total tiled surface.

Porcelain-Enameled Metal Panels

Porcelain enamel is a combination of glass and inorganic color oxides that are fused to metal 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. These are:

- Appearance Properties (PEI 501),
- Mechanical and Physical Properties (PEI 502),
- Resistance to Corrosion (PEI 503),
- High Temperature Properties (PEI 504), and
- 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; for walls, fiberglass boards are frequently used. The attributes of porcelain-enameled panels are similar to those for ceramic tile previously discussed; they are durable, easily washed, reflective, and come in a variety of colors. As with ceramic tile, these panels are not good for sound attenuation.

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, reflective ability, and low shrinkage. Experience has shown that these coatings do not withstand the harsh tunnel environmental conditions as well as the others, resulting in the need to repair or rehabilitate more often.

Miscellaneous Finishes

There are a variety of other finishes that can be used on the walls or ceilings of tunnels. Some of these finishes are becoming more popular due to their improved sound absorptive properties, ease of replacement, and ability to capitalize on the benefits of some of the materials mentioned previously. Some of the systems are listed in the following.

Coated Cement-Board Panels. These panels are not widely used in American tunnels at this time, but they offer a lightweight, fiber-reinforced cement board that is coated with baked enamel.

Precast Concrete Panels. This type of panel is often used as an alternative to metal panels; however, a combination of the two is also possible where the metal panel is applied as a veneer. Generally, ceramic tile is cast into the underside of the panel as the final finish.

Metal Tiles. This tile system is uncommon, but has been used successfully in certain tunnel applications. Metal tiles are coated with porcelain enamel and are set in mortar similarly to ceramic tile.

A.2 Ventilation Systems

A.2.1 Types

Tunnel ventilation systems can be categorized into five main types or any combination of these five. The five types are:

- Natural ventilation,
- Longitudinal ventilation,
- Semi-transverse ventilation,
- Full-transverse ventilation, and
- Single-point extraction.

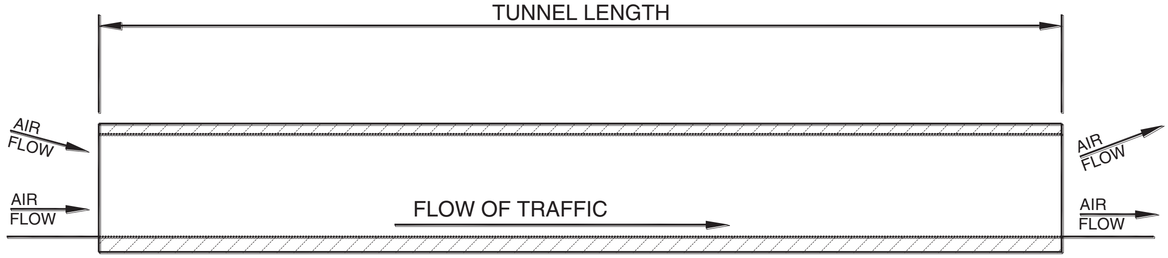
It should be noted that ventilation systems are more applicable to highway tunnels due to high concentrations of contaminants. For further information on tunnel ventilation systems refer to NFPA 502.

Natural Ventilation

A naturally ventilated tunnel is as simple as the name implies. The movement of air is controlled by meteorological conditions and the piston effect created by moving traffic pushing the stale air through the tunnel. This effect is minimized when bidirectional traffic is present. The meteorological conditions include elevation and temperature differences between the two portals as well as wind blowing into the tunnel. Figure A-8 shows a typical profile of a naturally ventilated tunnel. Another configuration would be to add a center shaft that allows for one more portal by which air can enter or exit the tunnel. Many naturally ventilated tunnels over 180 m (600 ft) in length have mechanical fans installed for use during a fire emergency.

Longitudinal Ventilation

Longitudinal ventilation is similar to natural ventilation but with the addition of mechanical fans, either in the portal buildings, the center shaft, or mounted inside the tunnel. Longitudinal ventilation is often used inside rectangular tunnels that do not have the extra space above the ceiling or below the roadway for ductwork. Also, shorter circular tunnels may use the longitudinal system since there is less air to replace and there is no need for even distribution of air through ductwork. The fans can be reversible and are used to move air into or out of the tunnel. Figure A-9 shows two different configurations of longitudinally ventilated tunnels.

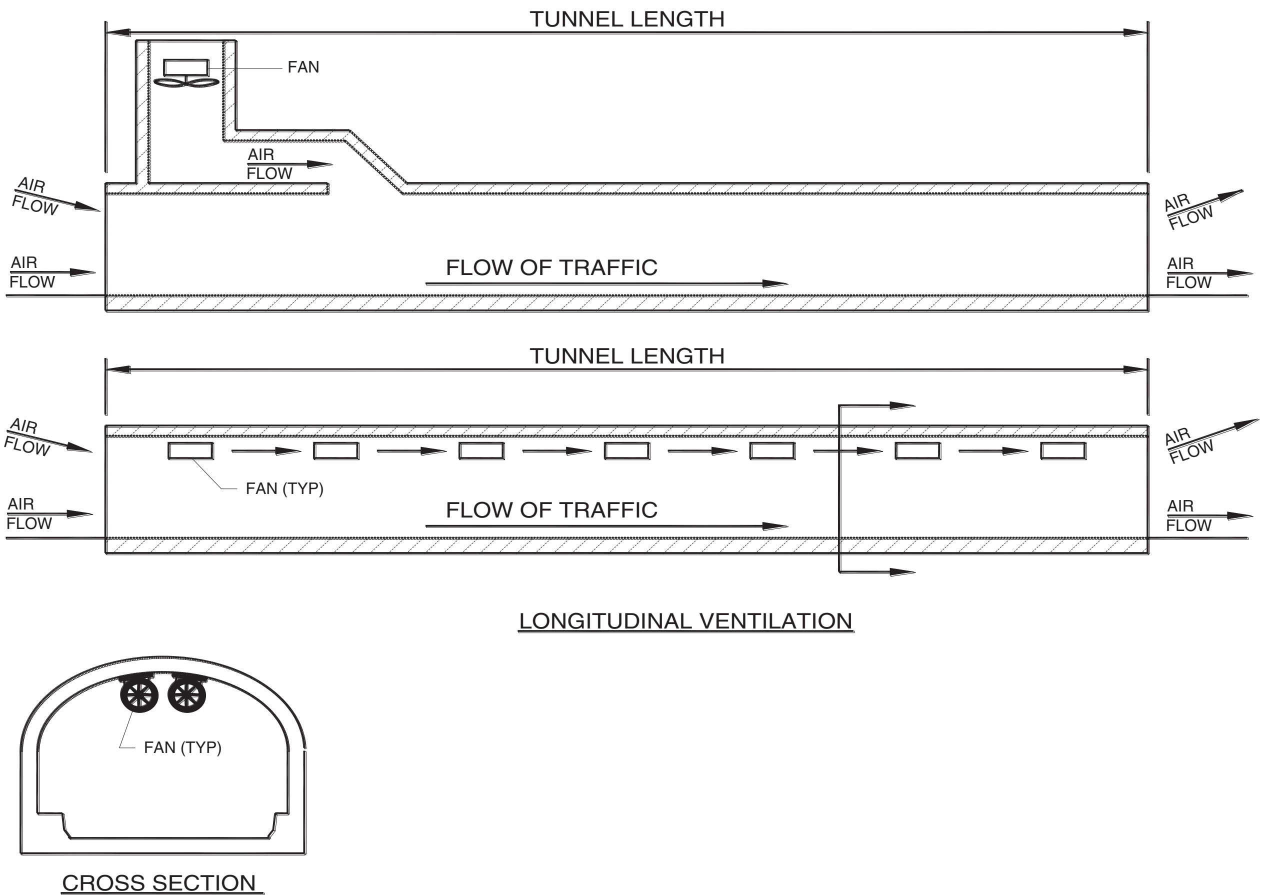


Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-8. Natural ventilation.

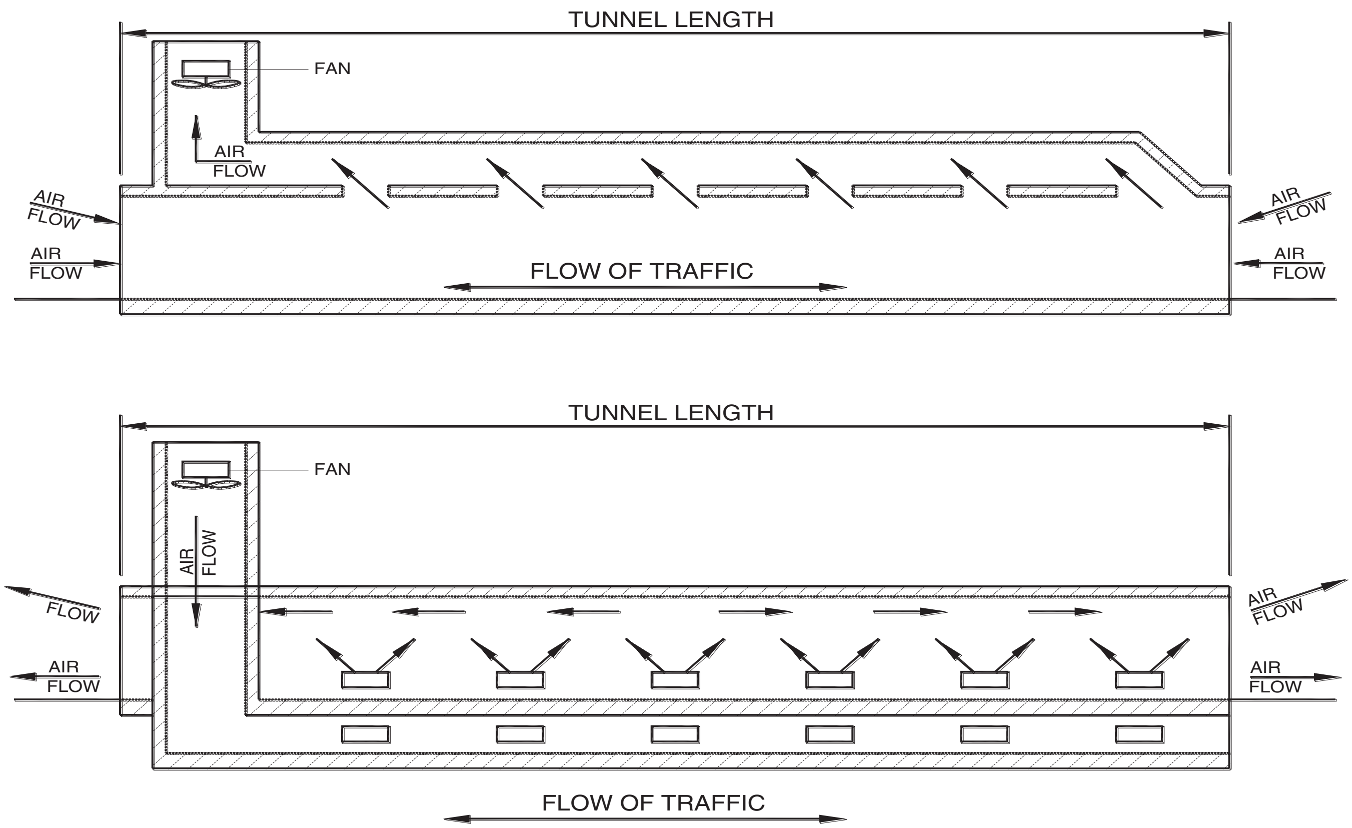
Semi-Transverse Ventilation

Semi-transverse ventilation also makes use of mechanical fans for movement of air, but it does not use the roadway envelope itself as the ductwork. A separate plenum or ductwork is added either above or below the tunnel with flues that allow for uniform distribution of air into or out of the tunnel. This plenum or ductwork is typically located above a suspended ceiling or below a structural slab within a tunnel with a circular cross-section. Figure A-10 shows one example of a supply-air semi-transverse system and one example of an exhaust-air semi-transverse system. It should be noted that there are many variations of a semi-transverse



Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-9. Longitudinal ventilation.



Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-10. Semi-transverse ventilation.

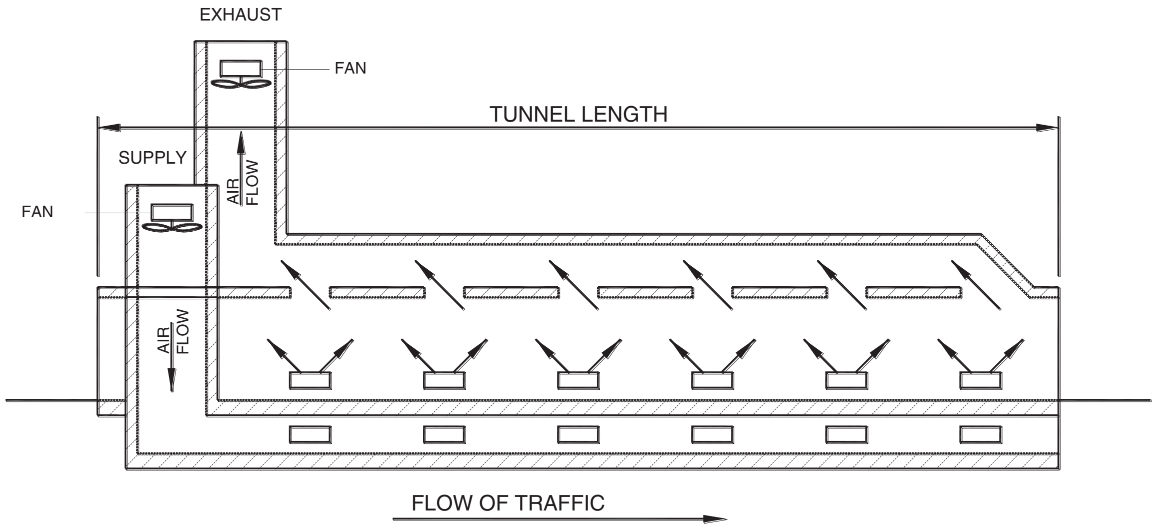
system. In one such variation, half the tunnel uses a supply-air system and the other half an exhaust-air system. Another variation is to have supply-air fans housed at both ends of the plenum that push air directly into the plenum, toward the center of the tunnel. One last variation is to have a system that can use either exhaust air or supply air by using reversible fans or a louver system in the ductwork that can change the direction of the air. In all cases, air either enters or leaves at both ends of the tunnel (bidirectional traffic flow) or at one end only (unidirectional traffic flow.)

Full-Transverse Ventilation

Full-transverse ventilation uses the same components as semi-transverse ventilation, but it incorporates supply air and exhaust air together over the same length of tunnel. This method is used primarily for longer tunnels that have large amounts of air that need to be replaced or for heavily traveled tunnels that produce high levels of contaminants. The presence of supply and exhaust ducts allows for a pressure difference between the roadway and the ceiling; therefore, the air flows transverse to the tunnel length and is circulated more frequently. This system may also incorporate supply or exhaust ductwork along both sides of the tunnel instead of at the top and bottom. Figure A-11 shows an example of a full-transverse ventilation system.

Single-Point Extraction

In conjunction with semi- and full-transverse ventilation systems, single-point extraction can be used to increase the airflow potential in the event of a fire in the tunnel. The system works by allowing the opening size of select exhaust flues to increase during an emergency. This can be



Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

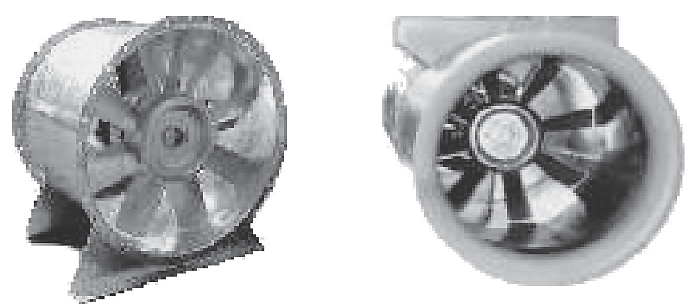
Figure A-11. Full-transverse ventilation.

done by mechanically opening louvers or by constructing portions of the ceiling out of material that would go from a solid to a gas during a fire, thus providing a larger opening. Both of these methods are rather costly and seldom used. Newer tunnels achieve the same results simply by providing larger extraction ports at given intervals that are connected to the fans through the ductwork.

A.2.2 Equipment

Fans

Axial. There are two main types of axial fans (see Figure A-12)—tube axial fans and vane axial fans. Both types move air parallel to the impellor shaft, but the difference between the two is the addition of guide vanes on one or both sides of the impellor for the vane axial fans. These additional vanes allow the fan to deliver pressures approximately four times that of a typical tube axial fan. The two most common uses of axial fans are to mount them horizontally on the ceiling at given intervals along the tunnel or to mount them vertically within a ventilation shaft that exits to the surface.



Tube Axial Fan Vane Axial Fan

Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-12. Axial fans.

Source: FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

Figure A-13. Centrifugal fan.

Centrifugal. This type of fan (see Figure A-13) outlets the air in a direction that is 90° to the direction at which air is obtained. Air enters parallel to the shaft of the blades and exits perpendicular to that. For tunnel applications, centrifugal fans can either be backward-curved or airfoil-bladed. Centrifugal fans are predominantly located within ventilation or portal buildings and are connected to supply or exhaust ductwork. They are commonly selected over axial fans due to their higher efficiency, with less horsepower required, and are therefore less expensive to operate.

Supplemental Equipment

Motors. Electric motors are typically used to drive the fans. They can be operated at either constant or variable speeds depending on the type of motor. According to the National Electric Manufacturers Association, motors should be able to withstand a voltage and frequency adjustment of ± 10%.

Fan Drives. A motor can be connected to the fan either directly or indirectly. Direct drives are where the fan is on the same shaft as the motor. Indirect drives allow for flexibility in motor location and are connected to the impellor shaft by belts, chains, or gears. The type of drive used can also induce speed variability for the ventilation system.

Sound Attenuators. Some tunnel exhaust systems are located in regions that require the noise generated by the fans to be reduced. This can be achieved by installing cylindrical or rectangular attenuators, mounted either directly to the fan or within ductwork along the system.

Dampers. Objects used to control the flow of air within the ductwork are considered dampers. They are typically used in a fully open or fully closed position but can also be operated at some position in between to regulate flow or pressure within the system.

A.3 Lighting Systems

A.3.1 Types

There are various light sources that are used in tunnels to make up the tunnel lighting systems. These include fluorescent, HPS, low-pressure sodium, metal halide, and pipe lighting, which is a system that may use one of the preceding light source types. Systems are chosen based on their life-cycle costs and the amount of light that is required for nighttime and daytime illumination. Shorter tunnels will require less daytime lighting due to the effect of light entering the portals on both ends, whereas longer tunnels will require extensive lighting for both nighttime and daytime conditions. In conjunction with the lighting system, a highly reflective surface on the walls and ceiling, such as tile or metal panels, may be used.

Fluorescent lights typically line the entire roadway tunnel length to provide the appropriate amount of light. At the ends of the roadway tunnel, low-pressure sodium lamps or high-pressure sodium lamps are often combined with the fluorescent lights to provide higher visibility when drivers' eyes are adjusting to the decrease in natural light. The transition length of tunnel required for having a higher lighting capacity varies from tunnel to tunnel and depends on which code the designer uses.

Both HPS lamps and metal halide lamps are also typically used to line the entire length of roadway tunnels. In addition, pipe lighting, usually consisting of HPS or metal halide lamps and longitudinal acrylic tubes on each side of the lamps, are used to disperse light uniformly along the tunnel length.

APPENDIX B

Catalog of Preservation Actions

Guide for the Preservation of Highway Tunnel Systems

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
LIFE SAFETY SYSTEMS												
Fire Protection												
Inspect manual fire alarm boxes			X						X		X	
Closed-circuit TV (CCTV) – confirm operation	X								X			
Automatic fire detectors				X					X		X	
Upgrade fire detection/alarm system head-end												X
Upgrade CCTV head-end												X
Fire Extinguishers												
Inspect each fire extinguisher in the tunnel and support spaces			X						X		X	
Perform maintenance on each fire extinguisher in the tunnel and support spaces						X			X		X	
If in a cabinet, confirm operation of cabinet door – door must latch securely and open freely			X						X			
Lubricate/repair/adjust door handle and hinges as necessary			X							X		
Fire Standpipes												
Fire department connections capped and clear				X					X			
Confirm threads are undamaged and caps in place				X					X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Test flow hydrants				X					X			
Test flow standpipe per NFPA 25						X			X		X	
Confirm top nut and caps are tight but not over-torqued				X					X			
Fire Hydrants												
Grease top nut					X				X			
Confirm cap is in place					X				X			
Test flow hydrant						X			X		X	
Confirm top nut and caps are tight but not over-torqued					X				X			
Fire Lines												
Freeze-Protection Pumps												
Clean and visually inspect				X					X			
Lubricate and grease pumps								X	X			
Operate pumps, confirm operation (prior to heating season)						X			X			
Heat tracing – verify system operation (prior to system operation)						X			X			
Pipe insulation with heat tracing – verify condition (prior to system operation)						X			X			
Test and confirm operation of low-temperature alarms (prior to heating season)						X			X	X		

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non- Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Fire Pumps												
Visually inspect fire pump		X							X			
Operate pump – (no-flow condition); note unusual noises or vibrations		X							X		X	
Operate pump – flow condition/flow test						X			X		X	
Lubricate pump, motor, and coupling								X	X			
Operate pump and measure current					X				X			
Check shaft alignment and shaft endplay					X				X			
Check and correct pressure gauges as required					X				X			
Measure motor and pump vibration				X					X			
Fire Pump Controller												
Exercise disconnect switch and circuit breaker		X							X			
Operate pumps from both alternate and primary power supplies		X							X			
Conduct annual test of system including flow and no-flow conditions in accordance with NFPA 72						X			X		X	
Fire Tank Fill Pump												
Visually inspect pump		X							X			
Operate pump – note unusual noises or vibrations				X					X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Lubricate pump, motor, and coupling				X					X			
Check shaft alignment and shaft endplay				X					X			
Inspect and test automatic tank fill valve						X			X		X	
Secondary containment provided for all hazardous materials		X							X		X	
MSDSs (material safety data sheets) for all materials posted (on file)					X				X		X	
Inspect all floors for oil leakage; add absorbent and clean as required to maintain safe footing	X								X			
Fire Alarm System												
Perform all tests and inspections in accordance with NFPA 72						X			X		X	
Make and file a permanent record of all inspections and tests conducted						X			X		X	
Open primary power supply to fire alarm panel and note sounding of trouble alarm and light		X							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							X			
Visually inspect all supervisory and water flow alarms on any standpipe systems		X							X			
Test all heat detectors with a calibrated heat source and replace all failed units					X					X		
Test all smoke detectors by measuring and recording sensitivity; replace all failed units					X				X			
Replace all failed smoke detector units										X		

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Clean all smoke and heat detector housings and check battery voltage under load					X				X			
Verify that proper alarm devices operate for the appropriate initiating device circuit					X				X			
Verify that all remote annunciators operate				X					X			
Check all lamps, alarm devices, and printers for proper operation				X					X			
Make a discharge test of batteries to determine capacity for operating system for 24 hours					X				X			
Upgrade fire detection/alarm system head-end											X	X
Communications												
Visual inspection of radio	X								X			
Visual inspection of telephone	X								X			
Test operation of radio			X						X			
Test operation of telephone			X						X			
Egress												
Emergency egress		X							X			
Exit lighting/signage/identification		X							X			
Tenable environment (Note: smoke control ventilation is located in fire suppression section.)		X							X		X	

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Emergency exits		X							X		X	
Cross-passageways		X							X		X	
Electrical												
Emergency lighting			X						X		X	
Power			X						X			
Redundant power			X						X			
Security plan			X						X		X	
Emergency Response Plan (ERP)												
ERP on file and all personnel aware of requirements					X				X		X	
ERP reviewed and updated periodically					X				X		X	
Tunnel personnel training of execution of ERP			X						X		X	
Training exercises with participating agencies						X			X		X	
Hydrocarbon Detector												
Confirm hydrocarbon detector will initiate both local and remote alarms								X	X			

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Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
CO Monitoring Equipment												
Tunnel (local) sensors (confirm calibration and/or sensor replacement)								X	X			
Vacuum tubing (leak test)				X					X			
Vacuum pump (lubrication)				X					X			
Central sensor								X	X			
System calibration (as required by individual system)								X	X		X	
Comparison gas refill (as required)								X	X		X	
Life Safety and Fire Code Issues (Flammable/Hazardous Materials)												
Verify that all safety guards and covers (belt, chain, electrical panel) are in place and secure		X							X		X	
Verify that no plastic (PVC, CPVC) pipe is located in supply-air passage					X				X		X	
Verify that all batteries are properly stored and vented; confirm that battery charging only taking place in well-ventilated spaces		X							X		X	
Verify that flammable material is stored in proper containers and properly ventilated spaces		X							X		X	
Verify that secondary containment is provided for all hazardous materials		X							X		X	
Verify MSDS sheets for all materials posted (on file)					X				X		X	
Inspect all floors for oil leakage; add absorbent and clean as required to maintain safe footing	X								X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
ELECTRICAL												
Closed-Circuit TV Camera												
Clean, align, and focus all cameras after tunnel washing					X				X			
Check cable connections to camera (i.e., power, control, video signal)					X				X			
Emergency Lighting												
Operate test buttons on emergency light fixtures		X							X			
Operate battery pack for emergency lighting for 90 minutes						X			X			
Electrical Switchboard and Switchgear												
Inspect switchgear bus and connections by infrared scanning						X			X			
Perform ultrasonic inspection of medium-voltage switchgear bus supports, insulators, and barriers						X			X			
Visually inspect all equipment for unusual conditions						X			X			
Inspect and check tightness of all connections						X			X			
Remove and replace defective lighting contacts						X				X		
Review results of last visual, infrared, and ultrasonic inspection								X	X			
After power shutdown, clean entire switchgear interior								X	X			
Clean all bus insulators and check for cracks and chips								X	X			

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Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Clean, lubricate (if applicable), and verify operation of all control switches, auxiliary relays, and devices								X	X			
Clean, lubricate, adjust, and add anti-oxidant grease to contacts of all disconnect switches								X	X			
Clean and perform insulation resistance testing on all lightning arrestors								X	X			
Perform insulation resistance testing on any bus bars								X	X			
Perform calibration test and verify proper operation of all meters								X	X			
Replace electromechanical-type protective relays with microprocessor-based relays										X		
Replace breakers with new and/or re-manufactured units												X
Low-Voltage Air Circuit Breakers												
Remove covers and thoroughly clean each breaker and contact surfaces								X	X			
Apply anti-oxidant grease to breaker's main contacts								X	X			
Lubricate and verify operation of all mechanisms								X	X			
Apply current equal to 90% to 110% of the breaker trip coil setting to verify proper pick-up of tripping mechanism								X	X			
Record trip times for long-time, short-time instantaneous, and ground fault breakers when passing loads equal to multiples of their listed ratings through each phase of the breaker								X	X			
Measure contact resistance and adjust where possible								X	X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Perform and record results of insulation resistance test from each pole to other two poles and to ground								X	X			
Clean and lubricate breaker carriage and racking mechanism on any draw-out breakers								X	X			
Upgrade breaker trip units												X
Molded-Case Circuit Breakers												
Inspect breaker for proper installation								X			X	
Remove cover (if possible) and fully clean interior and exterior								X	X			
Inspect for burning, overheating, wear, and proper alignment								X	X			
Perform contact resistance and insulation resistance measurements and test								X	X			
Apply current equal to 300% of breaker rating to test the long-time element								X	X			
Test and compare any breakers with instantaneous trip units to manufacturer's characteristic curve								X	X			
Automatic Transfer Switch (600-Volt Class)												
After total outage is obtained, clean all contact surfaces, apply anti-oxidant contact grease, measure and record contact resistance, and make adjustments if necessary								X	X			
Lubricate bearings, links, pins, and cams								X	X			

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Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Perform insulation resistance test								X	X			
Test all settings of voltage, frequency sensing, and timing relays								X	X			
Low-Voltage Insulated Cable (Less Than 600 Volts)												
Check all cable terminations for tightness								X	X			
Perform and record results of insulation resistance test from each phase to the other two and to ground for 1 minute using a test voltage of 1,000 volts direct current (DC); compare results with previous tests								X	X			
Electrical Transformer (All Types)												
Inspect transformer connections by infrared scanning						X			X			
Perform ultrasonic inspection of medium-voltage bus supports, insulators, and barriers						X			X			
Visually inspect all equipment for unusual conditions						X			X			
Test transformer and circuit breaker insulating oil						X			X			
Dry-Type Transformer												
Remove cover and visually inspect all cable/bus connections for evidence of overheating or burning; check for tightness and clean windings								X	X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Liquid-Filled Transformer												
Inspect transformers for leaks, deteriorated seals/gaskets, proper oil level, and test oil sample								X	X			
Inspect transformer tank and cooling fins for corrosion, chipped paint, dents, and proper connection to ground								X	X			
Inspect all bushings for cracks/chips, proper tightness, and evidence of overheating								X	X			
Inspect all gauges and alarm devices								X	X			
Clean core, coils, and enclosures and inspect any filters								X	X			
Perform primary and secondary insulation resistance test where possible								X	X			
Perform polarization index test on transformers 500 KVA and larger								X	X			
Perform turns ratio tests								X	X			
Perform calibration test and verify proper operation of all meters								X	X			
Generator												
Operate unit under load for 4 hours and check lubrication levels		X							X			
Change oil, coolant, and filter				X					X			
Compare nameplate information and connection with drawings and specifications				X					X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Inspect for proper anchorage and grounding				X					X			
Perform insulation resistance test on generator winding with respect to ground and determine polarization index				X					X			
Perform phase rotation test to determine compatibility with load requirements				X					X			
Functionally test engine shutdown and alarm controls for low oil pressure, over temperature, over speed, and other features				X					X			
Perform vibration baseline test and plot amplitude versus frequency for each main bearing cap				X					X			
Perform load bank test and record voltage, frequency, load current, oil pressure, and coolant temperature at periodic intervals during test				X					X			
Monitor and verify correct operation and timing of normal voltage-sensing relays, engine start sequence, time delay upon transfer, alternate voltage-sensing relays, automatic transfer operation, interlocks, limit switch functions, time delay and retransfer upon normal power restoration, and engine cool down and shutdown feature				X					X			
High Voltage Disconnect												
Inspect disconnect switch bus and connections by infrared scanning						X			X			
Perform ultrasonic inspection of medium-voltage bus supports, insulators, and barriers						X			X			
Visually inspect all equipment for unusual conditions						X			X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Busing Inspection												
Review results of last visual, infrared, and ultrasonic inspection								X	X			
Check for proper tightness of all exposed bus connections								X	X			
Thoroughly clean and check for cracks/chips of all bus insulators								X	X			
Clean, lubricate (if applicable), and verify operation of all control switches, auxiliary relays, and devices								X	X			
Clean, lubricate, adjust, and add anti-oxidant grease to contacts of all disconnect switches								X	X			
Clean and perform insulation resistance test on all lightning arrestors								X	X			
Perform insulation resistance test on any bus bars								X	X			
Service Enclosed Air Break Switches												
After shutdown, clean and inspect entire switch mechanism								X	X			
Check switch contacts for proper alignment and apply anti-oxidant grease to main contacts								X	X			
Check switch's arcing contacts for proper opening sequence relative to main contacts								X	X			
Inspect fuses and record size and type used								X	X			
Clean all phase isolation barriers and check for contamination and corona damage								X	X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Thoroughly clean and check for cracks/chips of all insulators								X	X			
Clean and perform insulation resistance test on all lightning arrestors								X	X			
Inspect all ground connections								X	X			
Perform contact resistance and insulation resistance tests and record results								X	X			
Motor Control Center												
Inspect controller bus and connections by infrared scanning						X			X			
Perform ultrasonic inspection of medium-voltage bus supports, insulators, and barriers						X			X			
Visually inspect all equipment for unusual conditions						X			X			
Review results of last visual, infrared, and ultrasonic inspections								X	X			
After power shutdown, clean entire controller interior								X	X			
Check for proper tightness of all exposed bus connections								X	X			
Clean all bus insulators and check for cracks and chips								X	X			
Clean, lubricate (if applicable), and verify operation of all control switches, auxiliary relays, and devices								X	X			
Clean, lubricate, adjust, and add anti-oxidant grease to contacts of all disconnect switches								X	X			
Perform an insulating resistance and polarization test of the bus and the motor feeder with the motor connected								X	X			
Test overloads at 125% and 600% of rating against the tripping curve								X	X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Test all alarms and lights for proper feedback from devices						X			X			
Perform calibration test and verify proper operation of all meters								X	X			
Replace ventilation fan starters with variable frequency drives (VFDs) (Note: motor replacement or rewind may be required also.)												X
Lighting Relays and Contactors												
Clean all contacts and replace all worn and pitted contacts								X	X			
Check tightness of contactors								X	X			
Measure load current and verify proper operation								X	X			
Traffic/Lane Signals												
Inspect and verify operation of lane control devices		X							X			
Inspect and verify operation of variable message signs		X							X			
Clean, replace filter, tighten connections, replace lamps, etc.				X					X			
Tunnel Control System												
Check all controls on consoles for proper operation of tunnel lighting and fans						X			X			
Test all alarms and lights for proper feedback from devices						X			X			
Check all connections for tightness						X			X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Clean cabinets						X			X			
Replace computer [human–machine interface (HMI)] hardware								X				X
Upgrade control system software								X				X
Back up control system programs								X				X
Tunnel Vehicle Over-Height System												
Check for proper operation of over-height detectors				X					X			
Tunnel Lights												
Verify proper operation of the lighting fixtures in the tunnel areas	X								X			
Count and record number of lights out on night lighting and day lighting	X								X			
Replace any inoperable bulbs or ballasts with ones of similar or increased efficiency	X								X			
Clean exterior of lenses on all lighting fixtures in the tunnel				X					X			
If required, clean interior of lenses				X					X			
Inspect gasketing on fixtures						X			X			
Verify operation of portal light meters				X					X			
Verify operation of time clocks				X					X			
Perform group relamping for specific lamp types						X						X

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Upgrade lamps to newer sources as appropriate												X
Replace magnetic ballasts with high-efficiency electronic												X
Underground Tank and Piping Monitor												
Perform built-in test (if any) and verify that each circuit is operational; if not, identify circuit using troubleshooting guide and replace parts as necessary						X				X		
MECHANICAL												
Air Compressor												
Clean or replace air filters if necessary				X					X			
Clean external cooling fans				X					X			
Manually operate safety valves and drain tank				X					X			
Sample/analyze oil for contamination and change if necessary						X				X		
Check belt tension, clean motor, and operate safety valves on receiver						X				X		
Inspect system for air leaks						X				X		
Tighten or check all bolts and lubricate motor bearings								X	X			
Inspect and clean compressor valves						X			X			
Verify operation of low-level oil switch						X			X			
Inspect and confirm operation of all pressure-relief valves and safety controls as required						X			X		X	

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Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Air-Conditioning Unit												
Clean or replace air filters				X					X			
Check coils and clean if necessary						X			X			
Inspect controls and verify proper operation of unit						X			X			
Check and adjust as needed – fan-belt adjustment, tension				X						X		
Confirm operation of condenser and evaporator fans				X					X			
Confirm (refrigerant) pressures and temperatures						X			X			
Boilers (Furnaces)												
Check chimney and flue for obstructions and ensure all joints are well supported and properly sealed					X					X		
Lubricate pumps and motors as required					X				X			
Clean entire boiler, inside and out						X			X			
Replace fuel filter and oil atomizing nozzle						X			X			
Confirm water level(s)		X							X			
Restart boiler and test burner performance, flue gas CO_2, smoke, and temperature						X			X			
Verify operation of all limit switches and primary controls						X			X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Test relief valve or safety valve (use extreme caution)						X			X			
Check all steam traps for operation, leak-through			X						X			
High-efficiency (condensing) boilers only – service condensate neutralization trap; add limestone as required						X			X			
Inspect and confirm operation of all pressure-relief valves and safety controls as required						X			X		X	
Chiller												
Check for leaks (refrigerant and water)				X					X			
Check purge operation				X					X			
Check lubricant level(s)		X							X			
Check lubricant filter/pressure drop					X				X			
Confirm refrigerant level		X							X			
Confirm system pressure and temperatures				X					X			
Confirm that water flow matches design					X				X			
Confirm expansion valve operation				X					X			
Clean condenser and lubricant cooler					X				X			
Clean evaporator on open systems						X			X			
Calibrate pressure, temperature, and flow controls						X			X			

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Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Check all wires and power connections for tightness						X			X			
Inspect starter contacts and action						X			X			
Check all safety interlocks					X				X			
Dielectric check of motor						X			X			
Change lubricant dryer and filter						X			X			
Perform analysis of oil and refrigerant					X				X			
Inspect seals on open units for signs of leakage				X					X			
Partial or complete valve and/or bearing inspection, per manufacturer's recommendations								X		X		
Check vibration levels				X					X			
Check compressor guide vanes and linkage for operation, adjustment, and wear								X		X		
Perform eddy current inspection of heat exchanger tubes								X	X			
Compressor teardown and inspection of rotating parts								X		X		
Control System												
Confirm all status points (on/off, open/closed)					X				X			
Confirm control of individual equipment					X				X			
Check all alarms and safety interlocks			X						X			
Confirm feedback of operational points					X				X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Cooling Towers												
Check and lubricate pumps and fans					X				X			
Check safety controls						X			X			
Clean sump				X					X			
Sample (analyze water quality and add chemicals as indicated or as required)						X			X			
Domestic Water Pump and Tank												
Visually inspect pump (when accessible)		X							X			
Lubricate pump and motor						X			X			
Check pump operation in conjunction with well tanks						X			X			
Lubricate ejector pumps						X			X			
Measure water drawdown to verify proper operation						X			X			
Check air pressure in tank bladder and inflate as necessary					X					X		
Verify start and stop settings of pressure switch (differential should not exceed 25 psi)						X			X			
Drainage System (Roadway)												
Grate inspection (damage, blockage)			X							X		
Flush inlet and piping system					X				X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Dewatering Pumps (Fixed and Portable)												
Operate pumps – confirm operation		X							X			
Clean and visually inspect					X				X			
Lubricate pumps (prior to use for portable)						X			X			
Drainage System (Support Spaces)												
Grate inspection (damage, blockage)	X									X		
Flush inlet and piping system					X				X			
Emergency Eyewash												
If bacteria control solution is not used, flush and clean unit with pure water		X							X			
Drain unit and flush and clean the storage tank and refill with water and water treatment								X	X			
Emergency Generator												
Generator exercised			X						X			
Fuel lines inspected for leakage			X						X			
Fuel filter changed						X			X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Fuel sump drained					X				X			
Cooling air intake airflow confirmed – damper interlocks confirmed; no restrictions observed			X						X			
Cooling air discharge airflow confirmed – damper interlocks confirmed; no restrictions observed			X						X			
Environmental (Spill Prevention)												
Confirm all secondary containment (containment pallets, etc.) is in place and capacity is adequate				X					X		X	
Confirm spill response materials (oil-dry, absorptive socks, etc.) are available near storage areas and quantities are adequate for all spill scenarios				X							X	
Confirm MSDS for all materials are posted and/or on file				X							X	
Fans and Dampers (General Ventilation)												
Operate fans and motor-operated dampers and listen for unusual noises and vibrations		X							X			
Check and record bearing temperatures		X							X			
Lubricate shaft-bearing pillow blocks and motor bearings			X						X			
Inspect V-belts for proper adjustment			X						X			
Clean centrifugal wheel, inlet, and other moving parts						X			X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Fans (Tunnel Ventilation)												
Operate fans and motor-operated dampers and listen for unusual noises and vibrations		X							X			
Check and record bearing and drive temperatures (with handheld infrared thermometer); if elevated temperature readings are found, investigate equipment condition and/or lubricant condition and level	X								X			
Check and record bearing and drive vibration readings (with handheld device); investigate equipment with abnormally high vibration readings	X								X			
Check oil level in fan bearings; confirm breather vent is open on pillow block bearing	X								X			
Check oil level in chain drive enclosures (as applicable); confirm breather vent is open	X								X			
Clean electric motor, including cooling fan and air screen and passages					X				X			
General cleaning fan interior and exterior						X			X			
Disconnect motor from power supply and regrease, ensuring chamber is 75% full of grease				X					X			
Operate fan through entire range of speeds and note any noises or vibrations (balance fan if required)				X					X			
Inspect inside and outside of housing and impellor for wear, deterioration, or build-up of material				X					X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Inspect fan and motor mounting bolts, anchors, and connections for proper torque, failures, or damage				X					X			
Change oil in bearing pillow blocks and drive reservoirs; grease fan bearings as applicable								X	X			
Remove inspection cover from drive guard and inspect chain to verify proper lubrication and wear; adjust if necessary			X						X			
Have testing laboratory perform oil analysis, including testing for contaminants								X	X			
Verify damper interlocks operate properly through all positions				X					X			
Verify that any dampers operate properly through all positions; lubricate if necessary				X					X			
Dampers (Tunnel Ventilation)												
Operate motor-operated dampers and check for unusual noises and vibrations		X							X			
Check bearings for wear and dampers for debris			X						X			
Lubricate damper bearings and all linkages			X						X			
Clean damper blades and linkages						X			X			
Inspect air ducts and passages – clean out debris as necessary			X							X		

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Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Fuel-Oil Day Tank												
Inspect tank for damage, corrosion, or leakage on both inside and outside; perform during same week as boiler or generator inspection						X			X			
Gas-Fired Equipment (General)												
Gas train checked for leaks			X						X			
Confirm vent piping is vented to the outside of the structure and is clear of blockages			X						X			
Cycle gas blocking valve					X				X			
Verify operation of all safeties and limit switches			X						X			
Verify operation of primary controls			X						X			
Test burner performance, flue gas CO_2, smoke, and temperature						X	-		X			
Check condition of stack, power vent fan, associated equipment					X				X			
General Equipment												
Exercise valves – lubricate per manufacturer's recommendations				X					X			
Assess corrosion on all equipment and equipment supports; repair corrosion damage, properly prepare surface, and repaint equipment as required				X								X
Check for missing or loose mounting hardware and fasteners; re-torque or replace fasteners as necessary				X						X		

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Vibration isolation in good condition; no short-circuiting or vibration from moving equipment to structure observed				X					X			
Oil sight glasses and gauges clean, visibility (readability) good			X						X			
Vent holes on bearing vents clean; confirm accurate level readings		X							X			
Flexible connections on piping and ductwork in good condition with no holes or tears			X						X			
Verify all spaces clean with no debris to hinder operations		X								X		
All fill and vent caps in place to prevent entry of water or dirt into equipment	X									X		
Hot Water Pump												
Visually inspect plumbing connections for signs of corrosion				X					X			
Visually inspect exterior of water heater for signs of leakage				X					X			
Lubricate pump and motor as required								X	X			
Pressure Vessels												
Confirm that inspection by agency having jurisdiction is current and certificate is posted and/or on file					X						X	
Inspect vessel for signs of leakage		X							X			
Inspect vessel for signs of undue corrosion		X								X		

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Sump Pumps												
Visually inspect pump		X							X			
Operate pump – note unusual noises or vibrations		X							X			
Lubricate pump, motor, and coupling			X						X			
Operate pump and measure current					X				X			
Sump clean and free of debris; clean as necessary			X							X		
Confirm sump pit covered – no fall hazard		X								X		
Septic System												
Check tank level			X						X			
Pump out tank (as indicated or as required)							X		X			
Ejector Pumps												
Check local indications (verification of proper functioning from control panel)	X								X			
Visually inspect pumps						X			X			
Unit Heaters												
Clean unit casing, fan, diffuser, coil, and/or motor thoroughly, and clean and repaint any corrosion spots on casing						X				X		
Tighten the fan guard, motor frame, and fan bolts, and check fan clearances						X			X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Inspect any control panel wiring to ensure that the insulation is intact and that all connections are tight						X			X			
Examine all heater and relay contacts for pitting or burning and replace if necessary						X			X			
Lubricate motor if necessary								X	X			
Check operation controls						X			X			
Underground Fuel Oil Tank												
Confirm operation of liquid level sensor and low-level alarm						X			X			
Confirm operation of high-level alarm						X			X			
Check leak detection equipment for operation								X	X			
Variable Frequency Drives												
Verify that environmental conditions required by unit manufacturer are being met by equipment room HVAC equipment (typically 50–104°F)	X								X			
Verify that cooling air screens and passageways are clean and unobstructed		X							X			
Water Storage Tank (Fire Protection)												
Visually inspect tank exterior				X						X	X	
Inspect water heating system and low-temperature alarm (monthly supervised, weekly unsupervised during heating season)		X	X						X		X	

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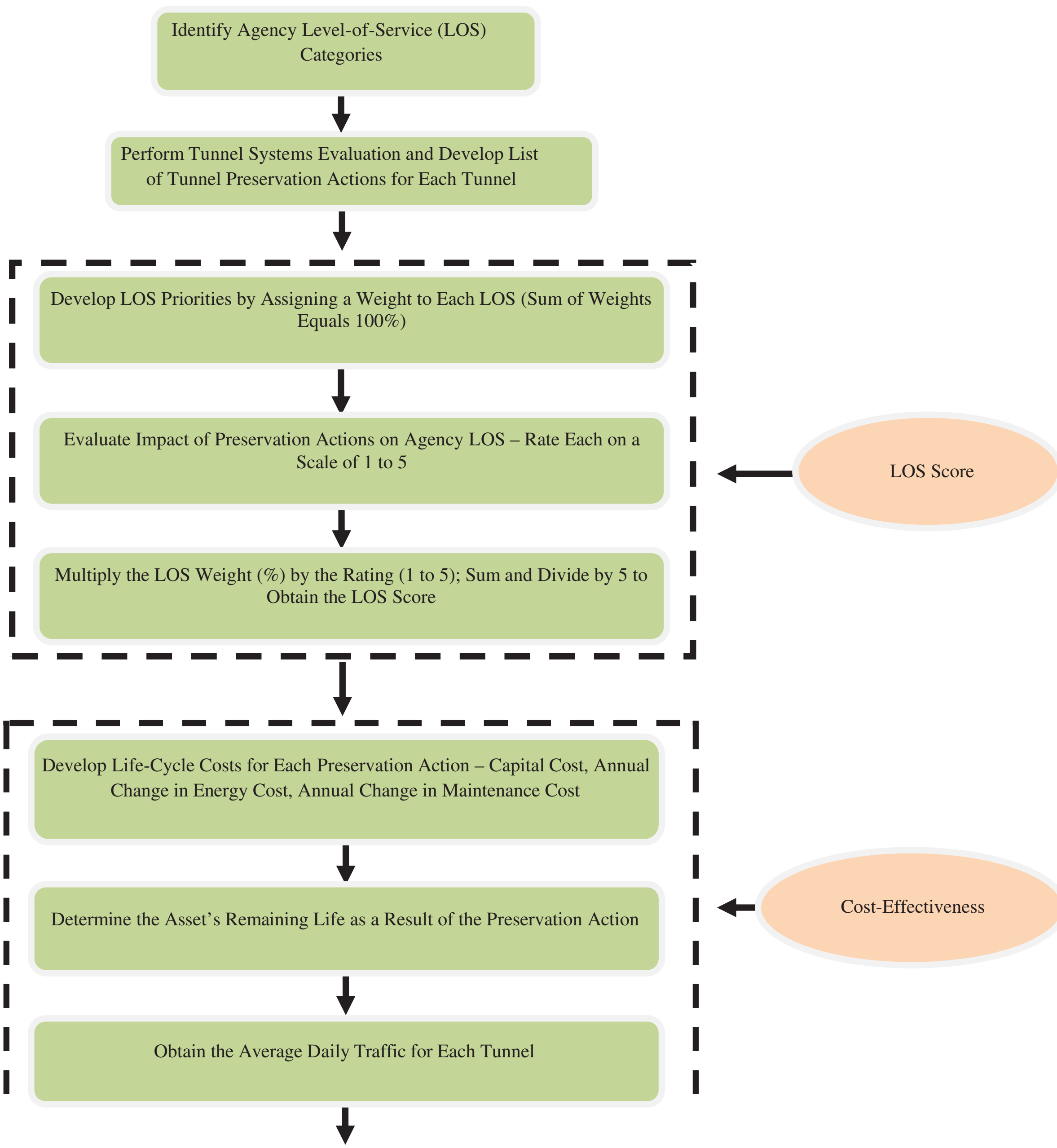
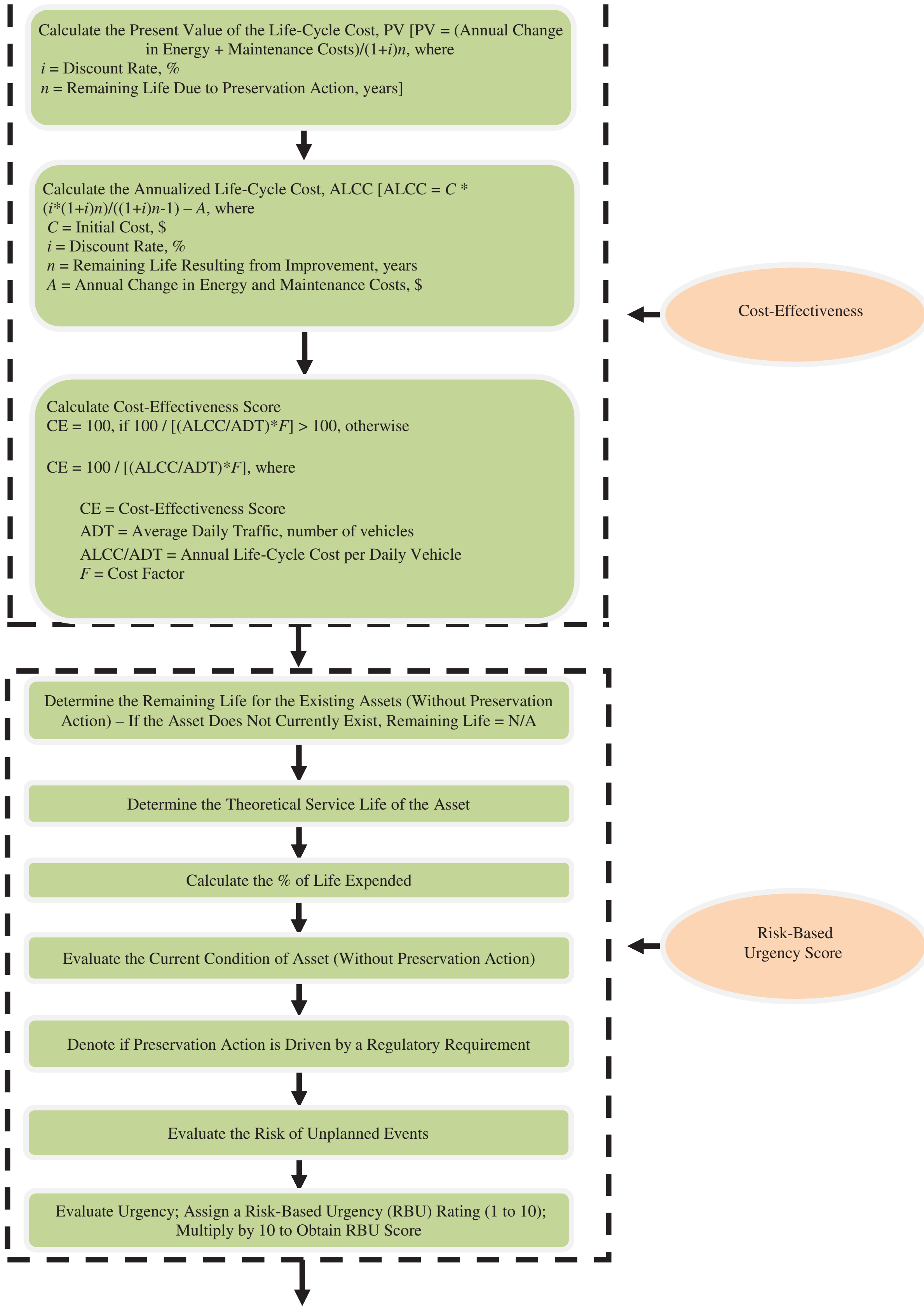
Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Inspect low-water-level alarm (quarterly supervised, monthly unsupervised)		X	X						X		X	
Inspect and test automatic tank fill valve						X			X		X	
Test high- and low-temperature alarms during heating season			X						X		X	
Test tank heating system prior to heating season						X			X		X	
Visually inspect tank interior (3 or 5 years per NFPA 25)										X	X	
STRUCTURAL												
Tunnel Structure												
Remove and replace delaminated tiles												X
Replace missing tiles												X
Remove bulging tiles												X
Repair spalls												X
Remove delaminated concrete												X
Repair active-leaking cracks to prevent further structure deterioration												X
Repair severe leakage through concrete liner, control joints, or expansion joints												X
Repair or replace deteriorated or failed expansion joints												X
Wash walls and ceiling				X					X			
Visually inspect walls, ceilings, slabs, pavements, walkways, stairs, etc., for structural deficiencies			X							X		

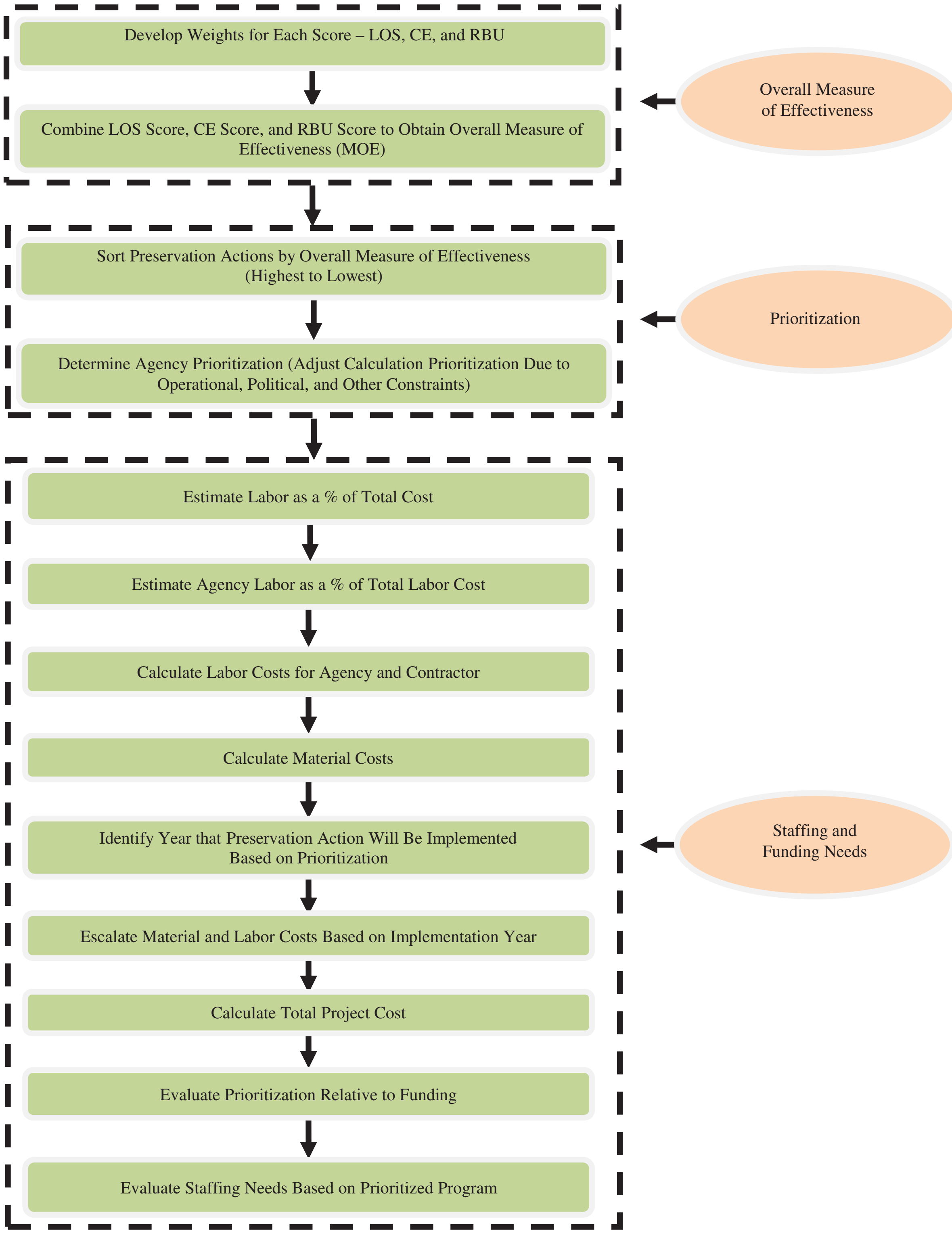
Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
	Daily	Weekly	Monthly	Quarterly	Semi-Annually	Annually	Biennially	Manufacturer's Recommendation	Cyclical (Non-Condition-Based) Preventive Maintenance	Condition-Based Preventive Maintenance	Regulatory	Rehabilitation
Remove icicles above travel roadway	X								X			
Replace damaged or deteriorated timbers in timber-lined tunnels												X
Install rock anchors at unstable rock locations in unlined rock tunnels												X
Repair leaking joints in sunken-tube tunnels												X
Roadway												
Repair or replace deteriorated structural roadway slabs												X
Repair or replace pavement wearing surfaces												X
Signs												
Visually inspect supports and readability of signs				X						X		

APPENDIX C

Highway Tunnel Preservation Prioritization Flowchart




Calculate the Present Value of the Life-Cycle Cost, PV [PV = (Annual Change in Energy + Maintenance Costs)/(1+i)n, where
i = Discount Rate, %
n = Remaining Life Due to Preservation Action, years]
Calculate the Annualized Life-Cycle Cost, ALCC [ALCC = C * (i*(1+i)n)/((1+i)n-1) – A, where
C = Initial Cost, $
i = Discount Rate, %
n = Remaining Life Resulting from Improvement, years
A = Annual Change in Energy and Maintenance Costs, $
Cost-Effectiveness
Calculate Cost-Effectiveness Score
CE = 100, if 100 / [(ALCC/ADT)*F] > 100, otherwise
CE = 100 / [(ALCC/ADT)*F], where
CE = Cost-Effectiveness Score
ADT = Average Daily Traffic, number of vehicles
ALCC/ADT = Annual Life-Cycle Cost per Daily Vehicle
F = Cost Factor
Determine the Remaining Life for the Existing Assets (Without Preservation Action) – If the Asset Does Not Currently Exist, Remaining Life = N/A
Determine the Theoretical Service Life of the Asset
Calculate the % of Life Expended
Evaluate the Current Condition of Asset (Without Preservation Action)
Risk-Based Urgency Score
Denote if Preservation Action is Driven by a Regulatory Requirement
Evaluate the Risk of Unplanned Events
Evaluate Urgency; Assign a Risk-Based Urgency (RBU) Rating (1 to 10); Multiply by 10 to Obtain RBU Score


Develop Weights for Each Score – LOS, CE, and RBU
Combine LOS Score, CE Score, and RBU Score to Obtain Overall Measure of Effectiveness (MOE)
Overall Measure of Effectiveness
Sort Preservation Actions by Overall Measure of Effectiveness (Highest to Lowest)
Determine Agency Prioritization (Adjust Calculation Prioritization Due to Operational, Political, and Other Constraints)
Prioritization
Estimate Labor as a % of Total Cost
Estimate Agency Labor as a % of Total Labor Cost
Calculate Labor Costs for Agency and Contractor
Calculate Material Costs
Identify Year that Preservation Action Will Be Implemented Based on Prioritization
Staffing and Funding Needs
Escalate Material and Labor Costs Based on Implementation Year
Calculate Total Project Cost
Evaluate Prioritization Relative to Funding
Evaluate Staffing Needs Based on Prioritized Program

APPENDIX D

Detailed Example

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 have been 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.

The agency has allocated $5,000,000 for the following fiscal year for the preservation of its tunnels. Across its entire transportation system, the agency has defined six LOS categories:

1. Reliability,
2. Safety,
3. Security,
4. Preservation,
5. Quality of service, and
6. Environment.

The tunnels in Table D-1 are owned and operated by the agency.

The tunnel 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 customers' complaints to the tunnel owner.

The full listing of preservation actions is evaluated for their impact on LOS (shown later in Table D-3; determination of LOS scores is explained in the following).

Level-of-Service Score

The first step to generate a prioritized list is to analyze how the actions affect the overall LOS. Each action is rated 1 (very little impact) to 5 (great impact) based on how it affects the six agency-established LOS goals. To generate a final LOS score, weights must be applied to the LOS categories based on agency priorities. After discussions, the AAMT has developed the following LOS weights. In the metric tool used, weighting is completed through percentages. All LOS weights should sum to 100%.

Table D-1. Agency X's tunnels.

Tunnel #	Average Daily Traffic (x1000)	Description
1	40	Rural tunnel on a major Interstate
2	100	High-traffic urban tunnel downtown in a major city
3	30	Low-traffic urban tunnel outside of city
4	19	Very-low-traffic urban tunnel downtown
5	50	Moderately high-traffic tunnel near Tunnel 2
6	75	High-traffic urban tunnel accessing a major city in close proximity to a river

Reliability:		20%
Safety:		40%
Security:		5%
Preservation:		18%
Quality of Service:		15%
Environment:		2%
Total	=	**100%** ✓ **OK**

To determine the LOS score for a preservation action, ratings for each LOS category are multiplied by the corresponding weight, summed, and then divided by 5 to achieve a score of between 0 and 100. Table D-2 provides an example showing the calculation of the LOS score for replacing the existing trench drains in Tunnel 1. 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.

$$\text{LOS score} = [1(20) + 3(40) + 0(5) + 3(18) + 2(15) + 4(2)]/5$$

$$\text{LOS score} = 232/5 = 46.4$$ ✓ **OK**

The remaining preservation actions were rated based on their impact on the six established levels of service. All 32 preservation actions, their ratings, and final calculated LOS scores are summarized in Table D-3.

Cost-Effectiveness Score

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 (the initial cost of the preservation action in present-value dollars; includes labor and equipment);

Table D-2. Example LOS ratings and LOS score.

Levels of Service		Reliability	Safety	Security	Preservation	Quality of Service	Environment	LOS Score (Eq. 5-1)
Weights		20%	40%	5%	18%	15%	2%	
Preservation Action	Tunnel #							
Replace existing trench drains	1	1	3	N/A	3	2	4	46.4

Table D-3. LOS ratings and LOS scores for all preservation actions.

Levels of Service		Reliability	Safety	Security	Preservation	Quality of Service	Environment	LOS Score (Eq. 5-1)
Weights		20%	40%	5%	18%	15%	2%	
Preservation Action	Tunnel #							
Ventilation upgrade to meet NFPA 502	1	1	5	1	5	1	N/A	**66.0**
Install new LED lights	1	3	4	2	5	4	5	**78.0**
CO system – repair to operating condition	2	2	5	N/A	4	N/A	2	**63.2**
Repair active leak in tunnel	4	4	5	N/A	5	5	N/A	**89.0**
Remove existing concrete tunnel ceiling	6	4	5	N/A	4	5	N/A	**85.4**
Install flood gates	6	4	4	N/A	5	N/A	N/A	**66.0**
Replace existing trench drains	1	1	3	N/A	3	2	4	**46.4**
Install manual fire alarm boxes	1	N/A	4	2	2	2	N/A	**47.2**
Install metal linear heat-detection cable system	1	N/A	5	1	3	N/A	N/A	**51.8**
Black hole effect – apply industrial coating to portals	1	N/A	3	N/A	1	4	N/A	**39.6**
Groundwater drainage relief hole installation	1	3	3	N/A	5	3	N/A	**63.0**
Repair/replace ceiling panels at seven locations	2	3	5	N/A	5	2	N/A	**76.0**
Remove and replace delaminated tile	2	2	3	N/A	5	2	N/A	**56.0**
Install lane signals every 300 ft within tunnel	2	4	5	1	N/A	4	N/A	**69.0**
Fire alarm system – repair heat wire to make operational	2	N/A	5	2	3	N/A	N/A	**52.8**
Remove and replace delaminated tile over the roadway	3	3	5	N/A	5	4	N/A	**82.0**
Remove and replace delaminated tile (walls)	3	2	3	N/A	5	3	N/A	**59.0**

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Table D-3. (Continued).

Levels of Service		Reliability	Safety	Security	Preservation	Quality of Service	Environment	LOS Score (Eq. 5-1)
Weights		20%	40%	5%	18%	15%	2%	
Preservation Action	Tunnel #							
Increase tunnel daytime light level	3	3	4	2	2	4	N/A	**65.2**
Replace expansion joint material in two locations	4	N/A	N/A	N/A	4	3	N/A	**23.4**
Replace fan #3 drive system	4	4	4	N/A	5	2	N/A	**72.0**
Install transient voltage surge suppressors	4	4	3	N/A	2	N/A	N/A	**47.2**
Repair spalled portal concrete and replace stone facing	5	N/A	5	N/A	5	5	N/A	**73.0**
Remove and replace delaminated wall tiles	5	N/A	3	N/A	5	2	N/A	**48.0**
Repair deluge system on exhaust fans	5	4	5	N/A	4	N/A	N/A	**70.4**
Replace fluorescent lights in electrical room	5	N/A	2	N/A	N/A	N/A	N/A	**16.0**
Install lane signals every 300 ft within tunnel	5	3	5	N/A	2	5	N/A	**74.2**
Repair spalled concrete tunnel barriers	6	N/A	1	N/A	3	2	N/A	**24.8**
Repair spalls on arch and walls	6	N/A	3	N/A	5	3	N/A	**51.0**
Install new CCTV cameras and system	6	3	4	5	N/A	2	N/A	**55.0**
Install over-height truck detection equipment and system, remove existing	6	4	3	1	4	2	N/A	**61.4**
Install oil–water separator	6	N/A	2	N/A	N/A	N/A	5	**18.0**
Rehabilitate and upgrade existing ventilation system	6	4	5	N/A	3	2	N/A	**72.8**

Note: N/A signifies that no rating was assigned to this LOS standard, and it is taken as a zero in the calculation.

Table D-4. Cost-effectiveness score worksheet.

Preservation Action (PA)	Tunnel #	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)
Replace existing trench drains	1	270,000	27,000	–3,000	227,656	40	40	9,849	0.25	**40.6**

- 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;
- Average daily traffic for each tunnel; and
- Service life after improvement.

See the cost-effectiveness score worksheet in Table D-4 for a summary of all input (white) and output (gray). The following example calculates all output values for the replacement of trench drains in Tunnel 1.

Present Value of Life-Cycle Cost (PV of LCC)

First, calculate the PV of all future savings (or expenditures) due to the annual change in costs. This must take into account the discount rate. Excel's PV function considers this through the "PMT" term. However, for complete understanding, see the following example to verify Excel's calculation.

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

where

Annual change in costs = $3000 (savings),
Discount rate, $i = 3\%$, and
Remaining life due to preservation action, $n = 40$ years.

Table D-5 shows a summary of the present value of all future savings assuming an annual savings of $3,000 at a discount rate of 3%.

PV of all annual savings = **$69,344.32**, therefore

PV of LCC = (capital cost + agency oversight cost) – (PV of all annual savings), and

PV of LCC = $270,000 + $27,000 – $69,344.32 = $227,655.68, rounded to **$227,656 ✓ OK**.

Since the remaining life due to the preservation actions varies greatly, annualizing the cost of the preservation action allows for a uniform comparison. Excel calculates the ALCC through the "PMT" function dependent on the present value, discount rate, and change in remaining life. The following long-hand calculation verifies Excel's results for the trench drain replacement in Tunnel 1.

Table D-5. PV of annual savings.

Year	Annual Savings	Year	Annual Savings	Year	Annual Savings
1	$2,912.62	16	$1,869.50	31	$1,199.96
2	$2,827.79	17	$1,815.05	32	$1,165.01
3	$2,745.42	18	$1,762.18	33	$1,131.08
4	$2,665.46	19	$1,710.86	34	$1,098.13
5	$2,587.83	20	$1,661.03	35	$1,066.15
6	$2,512.45	21	$1,612.65	36	$1,035.10
7	$2,439.27	22	$1,565.68	37	$1,004.95
8	$2,368.23	23	$1,520.08	38	$975.68
9	$2,299.25	24	$1,475.80	39	$947.26
10	$2,232.28	25	$1,432.82	40	$919.67
11	$2,167.26	26	$1,391.08		
12	$2,104.14	27	$1,350.57		
13	$2,042.85	28	$1,311.23		
14	$1,983.35	29	$1,273.04		
15	$1,925.59	30	$1,235.96		
				Total Savings	**$69,344.32**

Annualized Life-Cycle Cost

$$\text{ALCC} = C * \left[i * (1+i)^n\right] / \left[(1+i)^n - 1\right] - A$$

where

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

ALCC = ($270,000 + $27,000) ∗ [0.03(1 + 0.03)^{40}]/[(1 + 0.03)^{40}–1] – $3,000
ALCC = $9,848.93, rounded to **$9,849 ✓ OK**

Considering that each tunnel in the agency's system has a different ADT, the cost-effectiveness for each preservation action cannot be determined based on ALCC alone. Simply, the ALCC must be broken down further to an ALCC per average daily vehicle. The trench drains in Tunnel 1 are considered again in the following.

Annual Cost per Average Daily Vehicle

ACDV = ALCC/ADT

where

ACDV = annual cost per average daily vehicle, $,
ALCC = annualized life-cycle cost (previously calculated), $, and
ADT = average daily traffic (not in thousands), # of vehicles.

ACDV = $9,849/40,000 vehicles = $0.246, rounded to **$0.25 ✓ OK**

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. For more discussion on calibrating the cost-effectiveness score, see Section 5.3.4. As an example, the cost-effectiveness score for trench drains in Tunnel 1 is calculated in the following.

Cost-Effectiveness Score

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

$$CE = 100/[(ALCC/ADT)*10]$$

where

CE = cost-effectiveness score,
ADT = average daily traffic, total (input ADT is multiplied by 1,000), and
ALCC/ADT = annual life-cycle cost per daily vehicle.

CE = 100/[($9,849/40,000) * 10] = **40.6 ✓ OK**

Table D-6 shows a summary of all input (white) and output (gray) of the cost-effectiveness scores for all example preservation actions.

Table D-6. Cost-effectiveness scores for all preservation actions.

Preservation Action (PA)	Tunnel #	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)
Ventilation upgrade to meet NFPA 502	1	5,700,000	570,000	–152,500	3,614,495	25	40	207,573	5.19	**1.9**
Install new LED lights	1	3,400,000	136,000	–71,000	2,479,699	20	40	166,675	4.17	**2.4**
CO system – repair to operating condition	2	32,000	3,200	0	35,200	20	100	2,366	0.02	**100.0**
Repair active leak in tunnel	4	10,000	1,000	0	11,000	20	19	739	0.04	**100.0**
Remove existing concrete tunnel ceiling	6	8,000,000	800,000	–20,000	8,285,405	50	75	322,016	4.29	**2.3**
Install flood gates	6	8,000,000	320,000	0	8,320,000	100	75	263,300	3.51	**2.8**
Replace existing trench drains	1	270,000	27,000	–3,000	227,656	40	40	9,849	0.25	**40.6**
Install manual fire alarm boxes	1	235,000	23,500	0	258,500	20	40	17,375	0.43	**23.0**
Install metal linear heat-detection cable system	1	250,000	25,000	0	275,000	20	40	18,484	0.46	**21.6**

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Table D-6. (Continued).

Preservation Action (PA)	Tunnel #	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)
Black hole effect – apply industrial coating to portals	1	120,000	12,000	0	132,000	15	40	11,057	0.28	**36.2**
Groundwater drainage relief hole installation	1	1,596,000	159,600	–5,000	1,668,534	25	40	95,820	2.40	**4.2**
Repair/replace ceiling panels at seven locations	2	60,000	2,400	0	62,400	50	100	2,425	0.02	**100.0**
Remove and replace delaminated tile	2	170,000	17,000	0	187,000	50	100	7,268	0.07	**100.0**
Install lane signals every 300 ft within tunnel	2	400,000	40,000	0	440,000	20	100	29,575	0.30	**33.8**
Fire alarm system – repair heat wire to make operational	2	5,000	500	0	5,500	20	100	370	0.00	**100.0**
Remove and replace delaminated tile over the roadway	3	2,900	290	0	3,190	20	30	214	0.01	**100.0**
Remove and replace delaminated tile (walls)	3	78,000	7,800	–2,000	34,340	50	30	1,335	0.04	**100.0**
Increase tunnel daytime light level	3	502,000	50,200	–12,500	366,232	20	30	24,617	0.82	**12.2**
Replace expansion joint material in two locations	4	5,000	200	0	5,200	10	19	610	0.03	**100.0**
Replace fan #3 drive system	4	75,000	7,500	–2,500	45,306	20	19	3,045	0.16	**62.4**
Install transient voltage surge suppressors	4	24,000	960	0	24,960	20	19	1,678	0.09	**100.0**
Repair spalled portal concrete and replace stone facing	5	30,000	3,000	0	33,000	20	50	2,218	0.04	**100.0**
Remove and replace delaminated wall tiles	5	20,000	2,000	0	22,000	50	50	855	$0.02	**100.0**

Table D-6. (Continued).

Preservation Action (PA)	Tunnel #	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)
Repair deluge system on exhaust fans	5	280,000	28,000	0	308,000	20	50	20,702	$0.41	**24.2**
Replace fluorescent lights in electrical room	5	30,000	1,200	–1,000	16,323	20	50	1,097	0.02	**100.0**
Install lane signals every 300 ft within tunnel	5	110,000	4,400	0	114,400	20	50	7,689	0.15	**65.0**
Repair spalled concrete tunnel barriers	6	700,000	70,000	0	770,000	50	75	29,926	0.40	**25.1**
Repair spalls on arch and walls	6	1,000,000	100,000	0	1,100,000	50	75	42,752	0.57	**17.5**
Install new CCTV cameras and system	6	220,000	22,000	0	242,000	20	75	16,266	0.22	**46.1**
Install over-height truck detection equipment and system, remove existing	6	170,000	17,000	0	187,000	20	75	12,569	0.17	**59.7**
Install oil–water separator	6	90,000	9,000	0	99,000	20	75	6,654	0.09	**100.0**
Rehabilitate and upgrade existing ventilation system	6	3,700,000	370,000	0	4,070,000	20	75	273,568	3.65	**2.7**

Risk-Based Urgency Score

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 #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).

Table D-7. Example risk-based urgency scores.

Preservation Action	Tunnel #	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
Replace existing trench drains	1	2	40	95	3	N	1	5	**50.0**

- 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 then assign an RBU rating of from 1 to 10 considering all of the information collected. Table D-7 shows the RBU score input (white) and output (gray) for the trench drain replacement in Tunnel #1. See Table D-8 for a complete listing of the RBU score summary for all preservation actions.

% Life Expended

%LE = 100 * (original service life – remaining life)/original service life

%LE = 100 * (40 – 2)/40 = **95 ✓ OK**

Table D-8. Risk-based urgency scores for all preservation actions.

Preservation Action	Tunnel #	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
Ventilation upgrade to NFPA 502	1	1	25	96	2	Y	3	8	**80.0**
Install new LED lights	1	5	20	75	3	Y	1	3	**30.0**
CO system – repair to operating condition	2	2	20	90	4	Y	1	7	**70.0**
Repair active leak in ceiling	4	5	50	90	3	N	1	7	**70.0**
Remove existing concrete tunnel ceiling	6	0	50	100	3	N	1	10	**100.0**
Install flood gates	6	N/A	100	N/A	N/A	N	3	6	**60.0**
Replace existing trench drains	1	2	40	95	3	N	1	5	**50.0**
Install manual fire alarm boxes	1	N/A	N/A	N/A	N/A	Y	3	6	**60.0**
Install metal linear heat-detection cable system	1	N/A	N/A	N/A	N/A	Y	3	8	**80.0**
Black hole effect – apply industrial coating to portals	1	N/A	N/A	N/A	N/A	N	1	2	**20.0**

Table D-8. (Continued).

Preservation Action	Tunnel #	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
Groundwater drainage relief hole installation	1	N/A	N/A	N/A	4	N	1	7	**70.0**
Repair/replace ceiling panels at seven locations	2	2	50	96	2	N	1	6	**60.0**
Remove and replace delaminated tile	2	5	50	90	3	N	1	7	**70.0**
Install lane signals every 300 ft within tunnel	2	N/A	N/A	N/A	N/A	Y	1	4	**40.0**
Fire alarm system – repair heat wire to make operational	2	0	20	100	4	Y	3	10	**100.0**
Remove and replace delaminated tile over the roadway	3	5	50	90	4	N	2	8	**80.0**
Remove and replace delaminated tile (walls)	3	5	50	90	3	N	1	4	**40.0**
Increase tunnel daytime light level	3	5	20	75	2	Y	1	6	**60.0**
Replace expansion joint material in two locations	4	1	10	90	3	N	1	1	**10.0**
Replace fan #3 drive system	4	1	20	95	2	N	1	2	**20.0**
Install transient voltage surge suppressors	4	N/A	N/A	N/A	N/A	N	2	4	**40.0**
Repair spalled portal concrete and replace stone facing	5	2	40	95	2	N	1	1	**10.0**
Remove and replace delaminated wall tiles	5	1	50	98	2	N	1	4	**40.0**
Repair deluge system on exhaust fans	5	0	20	100	3	Y	3	8	**80.0**
Replace fluorescent lights in electrical room	5	2	20	90	2	N	1	1	**10.0**
Install lane signals every 300 ft within tunnel	5	N/A	N/A	N/A	N/A	Y	1	4	**40.0**
Repair spalled concrete tunnel barriers	6	2	50	96	2	N	1	2	**20.0**
Repair spalls on arch and walls	6	5	50	90	2	N	1	2	**20.0**
Install new CCTV cameras and system	6	N/A	N/A	N/A	N/A	N	1	5	**50.0**
Install over-height truck detection equipment and system, remove existing	6	0	20	100	4	N	3	8	**80.0**
Install oil–water separator	6	N/A	N/A	N/A	N/A	Y	1	3	**30.0**
Rehabilitate and upgrade existing ventilation system	6	1	25	96	2	Y	3	8	**80.0**

Note: The condition is rated as N/A whenever the proposed preservation action is installing a component that is new to the tunnel system.

Urgency Score

Urgency score = urgency * 10

Urgency score = 5 * 10 = **50.0 ✓ OK**

Table D-8 contains a summary of all input (white) and output (gray) for the RBU scores for all example preservation actions.

Overall Measure of Effectiveness

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 must add up to 100%. The AAMT has assigned the following weights to each score:

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

To calculate the overall measure of effectiveness, each score is multiplied by the applicable weight and summed. Table D-9 shows the results of this calculation for the trench drain example. The resulting MOE scores will be used to prioritize the improvements. For a complete summary of all scores, see Table D-10.

Overall Measure of Effectiveness

Total Score = 46.4 * (35/100) + 40.6 * (20/100) + 50.0 * (45/100)

Total Score = **46.9 ✓ OK**

Prioritization of Preservation Actions

Now that all of the preservation actions have been assigned a calculated priority based on total score, they can be sorted from highest to lowest priority. The user has the ability to 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 his or her 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 have an impact on safety. Table D-11 shows the full example of the user-defined prioritization of preservation actions.

Table D-9. Example measure of effectiveness scores.

Levels of Service		LOS Score	CE Score	RBU Score	MOE Score (Eq. 5-7)
Weights		35%	20%	45%	
Preservation Action	Tunnel #				
Replace existing trench drains	1	46.4	40.6	50.0	46.9

Table D-10. Measure of effectiveness scores for all preservation actions.

Levels of Service		LOS Score	CE Score	RBU Score	MOE Score
Weights		35%	20%	45%	
Preservation Action	Tunnel #				
Ventilation upgrade to meet NFPA 502	1	66.0	1.9	80.0	59.5
Install new LED lights	1	78.0	2.4	30.0	41.3
CO system – repair to operating condition	2	63.2	100.0	70.0	73.6
Repair active leak in ceiling	4	89.0	100.0	70.0	82.7
Remove existing concrete tunnel ceiling	6	85.4	2.3	100.0	75.4
Install flood gates	6	66.0	2.8	60.0	50.7
Replace existing trench drains	1	46.4	40.6	50.0	46.9
Install manual fire alarm boxes	1	47.2	23.0	60.0	48.1
Install metal linear heat-detection cable system	1	51.8	21.6	80.0	58.5
Black hole effect – apply industrial coating to portals	1	39.6	36.2	20.0	30.1
Groundwater drainage relief hole installation	1	63.0	4.2	70.0	54.4
Repair/replace ceiling panels at seven locations	2	76.0	100.0	60.0	73.6
Remove and replace delaminated tile	2	56.0	100.0	70.0	71.1
Install lane signals every 300 ft within tunnel	2	69.0	33.8	40.0	48.9
Fire alarm system – repair heat wire to make operational	2	52.8	100.0	100.0	83.5
Remove and replace delaminated tile over the roadway	3	82.0	100.0	80.0	84.7
Remove and replace delaminated tile (walls)	3	59.0	100.0	40.0	58.7
Increase tunnel daytime light level	3	65.2	12.2	60.0	52.3
Replace expansion joint material in two locations	4	23.4	100.0	10.0	32.7
Replace fan #3 drive system	4	72.0	62.4	20.0	46.7
Install transient voltage surge suppressors	4	47.2	100.0	40.0	54.5

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Table D-10. (Continued).

Levels of Service		LOS Score	CE Score	RBU Score	MOE Score
Weights		35%	20%	45%	
Preservation Action	Tunnel #				
Repair spalled portal concrete and replace stone facing	5	73.0	100.0	10.0	50.1
Remove and replace delaminated wall tiles	5	48.0	100.0	40.0	54.8
Repair deluge system on exhaust fans	5	70.4	24.2	80.0	65.5
Replace fluorescent lights in electrical room	5	16.0	100.0	10.0	30.1
Install lane signals every 300 ft within tunnel	5	74.2	65.0	40.0	57.0
Repair spalled concrete tunnel barriers	6	24.8	25.1	20.0	22.7
Repair spalls on arch and walls	6	51.0	17.5	20.0	30.4
Install new CCTV cameras and system	6	55.0	46.1	50.0	51.0
Install over-height truck detection equipment and system, remove existing	6	61.4	59.7	80.0	69.4
Install oil–water separator	6	18.0	100.0	30.0	39.8
Rehabilitate and upgrade existing ventilation system	6	72.8	2.7	80.0	62.0

Table D-11. Prioritization of preservation actions.

Levels of Service		LOS Score	CE Score	RBU Score	MOE Score	Calculated Priority	User-Defined Priority
Weights		35%	20%	45%	100%		
Preservation Action	Tunnel #						
Ventilation upgrade to meet NFPA 502	1	66.0	1.9	80.0	**59.5**	11	**6**
Install new LED lights	1	78.0	2.4	30.0	**41.3**	26	**18**
CO system – repair to operating condition	2	63.2	100.0	70.0	**73.6**	5	**8**
Repair active leak in ceiling	4	89.0	100.0	70.0	**82.7**	3	**7**
Remove existing concrete tunnel ceiling	6	85.4	2.3	100.0	**75.4**	4	**13**
Install flood gates	6	66.0	2.8	60.0	**50.7**	20	**16**

Table D-11. (Continued).

Levels of Service		LOS Score	CE Score	RBU Score	MOE Score	Calculated Priority	User-Defined Priority
Weights		35%	20%	45%	100%		
Preservation Action	Tunnel #						
Replace existing trench drains	1	46.4	40.6	50.0	**46.9**	24	**23**
Install manual fire alarm boxes	1	47.2	23.0	60.0	**48.1**	23	**14**
Install metal linear heat-detection cable system	1	51.8	21.6	80.0	**58.5**	13	**4**
Black hole effect – apply industrial coating to portals	1	39.6	36.2	20.0	**30.1**	31	**27**
Groundwater drainage relief hole installation	1	63.0	4.2	70.0	**54.4**	17	**22**
Repair/replace ceiling panels at seven locations	2	76.0	100.0	60.0	**73.6**	5	**9**
Remove and replace delaminated tile	2	56.0	100.0	70.0	**71.1**	6	**21**
Install lane signals every 300 ft within tunnel	2	69.0	33.8	40.0	**48.9**	22	**11**
Fire alarm system – repair heat wire to make operational	2	52.8	100.0	100.0	**83.5**	2	**1**
Remove and replace delaminated tile over the roadway	3	82.0	100.0	80.0	**84.7**	1	**2**
Remove and replace delaminated tile (walls)	3	59.0	100.0	40.0	**58.7**	12	**24**
Increase tunnel daytime light level	3	65.2	12.2	60.0	**52.3**	18	**15**
Replace expansion joint material in two locations	4	23.4	100.0	10.0	**32.7**	28	**32**
Replace fan #3 drive system	4	72.0	62.4	20.0	**46.7**	25	**19**
Install transient voltage surge suppressors	4	47.2	100.0	40.0	**54.5**	16	**26**
Repair spalled portal concrete and replace stone facing	5	73.0	100.0	10.0	**50.1**	21	**12**

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Table D-11. (Continued).

Levels of Service		LOS Score	CE Score	RBU Score	MOE Score	Calculated Priority	User-Defined Priority
Weights		35%	20%	45%	100%		
Preservation Action	Tunnel #						
Remove and replace delaminated wall tiles	5	48.0	100.0	40.0	**54.8**	15	**25**
Repair deluge system on exhaust fans	5	70.4	24.2	80.0	**65.5**	9	**3**
Replace fluorescent lights in electrical room	5	16.0	100.0	10.0	**30.1**	30	**30**
Install lane signals every 300 ft within tunnel	5	74.2	65.0	40.0	**57.0**	14	**10**
Repair spalled concrete tunnel barriers	6	24.8	25.1	20.0	**22.7**	32	**31**
Repair spalls on arch and walls	6	51.0	17.5	20.0	**30.4**	29	**28**
Install new CCTV cameras and system	6	55.0	46.1	50.0	**51.0**	19	**17**
Install over-height truck detection equipment and system, remove existing	6	61.4	59.7	80.0	**69.4**	8	**20**
Install oil–water separator	6	18.0	100.0	30.0	**39.8**	27	**29**
Rehabilitate and upgrade existing ventilation system	6	72.8	2.7	80.0	**62.0**	10	**5**

Evaluations of Funding and Staffing

To evaluate the preservation actions that can be accomplished within the funding limit, to identify funding needs for future years, or to evaluate the staffing needs for future years, further analysis is needed. 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.)

Contractor labor, materials, and agency oversight costs are calculated in the following for a project to replace trench drains. An escalation rate of 3% is assumed; the escalation rate is a user-input value that can be adjusted as required. These costs are calculated similarly for other preservation actions, as shown in Table D-12.

Labor cost = (% labor) ∗ capital cost

Labor cost = (60/100) ∗ $270,000 = **$162,000 ✓ OK**

Table D-12. Determining funding year for preservation actions.

User Priority	Tunnel #	Description	Total Cost ($)
1	2	Fire alarm system – repair heat wire to make operational	5,500
2	3	Remove and replace delaminated tile over the roadway	3,190
3	5	Repair deluge system on exhaust fans	308,000
4	1	Install metal linear heat-detection cable system	275,000
5	6	Rehabilitate and upgrade existing ventilation system	4,070,000
		TOTAL FUNDING YEAR 1	**4,661,690**

Labor cost with oversight = (labor cost) + (agency oversight)
Labor cost with oversight = \$162,000 + \$27,000 = \$189,000

Materials cost = (capital cost) – (labor cost)
Materials cost = \$270,000 – \$162,000 = **\$108,000 ✓ OK**

Subtotal cost = (labor cost with oversight) + (materials cost)
Subtotal cost = \$189,000 + \$108,000 = **\$297,000 ✓ OK**

Escalation = (subtotal cost) $*$ (1 + escal.)$^{(\text{funding year} - 1)}$ – (subtotal cost)
Escalation = \$297,000 $*$ (1 + 0.03)$^{(5-1)}$ – \$297,000 = **\$37,276 ✓ OK**

Total cost = (subtotal cost) + escalation
Total cost = \$297,000 + \$37,276 = **\$334,276 ✓ OK**

The agency has allocated \$5,000,000 for funding year 1 tunnel preservation actions. Therefore, based on the user's prioritization, the items in Table D-12 can be completed during funding year 1.

It is recommended that the user then analyze the calculated prioritization, total costs, and tunnel numbers when determining the final user priority. In effect, Table D-12 is the first iteration. For instance, perhaps the next iteration should consider tunnel locations, lane closure requirements, and staffing. Due to the high cost of rehabilitating and upgrading the existing ventilation system in Tunnel 6, perhaps the agency should consider completing other preservation actions having a high impact on safety that are less costly. This would allow it to accomplish more of its list and save the costly upgrade for when it has more funding.

The process outlined herein provides an initial means to compare and prioritize fundamentally different actions across a system of tunnels; the final prioritization is ultimately up to the user.

Using the agency cost information calculated for the prioritized preservation actions, it is possible to estimate the agency staffing needs to support the implementation of the improvements (see Table D-13). The man-hours for the agency staff involved in implementing the preservation actions can be determined by adding a new column for man-hours and dividing the agency cost by an average hourly rate for agency personnel. If the preservation action is to be implemented in the current year, enter 1 in the funding year column to negate escalation.

Table D-13. Total costs for funding and staffing.

User-Defined Priority	Preservation Action	Tunnel #	Capital Cost ($)	% Labor (0 to 100)	Labor Cost ($)	% Agency Labor (0 to 100)	Agency Labor Cost ($)	Agency Oversight Cost ($)	Total Agency Labor Cost ($)	Total Labor Cost with Agency Oversight ($)	Materials Cost ($)	Subtotal Cost ($)	Funding Year (1+)	Escalation ($)	Total Cost ($)
1	Fire alarm system – repair heat wire to make operational	2	5,000	50	2,500	0	–	500	500	3,000	2,500	5,500	1	–	5,500
2	Remove and replace delaminated tile over the roadway	3	2,900	75	2,175	0	–	290	290	2,465	725	3,190	1	–	3,190
3	Repair deluge system on exhaust fans	5	280,000	50	140,000	0	–	28,000	28,000	168,000	140,000	308,000	1	–	308,000
4	Install metal linear heat-detection cable system	1	250,000	60	150,000	0	–	25,000	25,000	175,000	100,000	275,000	1	–	275,000
5	Rehabilitate and upgrade existing ventilation system	6	3,700,000	20	740,000	0	–	370,000	370,000	1,110,000	2,960,000	4,070,000	1	–	4,070,000
6	Ventilation upgrade to meet NFPA 502	1	5,700,000	20	1,140,000	0	–	570,000	570,000	1,710,000	4,560,000	6,270,000	2	188,100	6,458,100
7	Repair active leak in ceiling	4	10,000	50	5,000	0	–	1,000	1,000	6,000	5,000	11,000	2	330	11,330
8	CO system – repair to operating condition	2	32,000	80	25,600	0	–	3,200	3,200	28,800	6,400	35,200	2	1,056	36,256

9	Repair/ replace ceiling panels at seven locations	2	60,000	50	30,000	100	30,000	2,400	32,400	32,400	30,000	62,400	2	1,872	64,272
10	Install lane signals every 300 ft within tunnel	5	110,000	50	55,000	0	–	11,000	11,000	66,000	55,000	121,000	2	3,630	124,630
11	Install lane signals every 300 ft within tunnel	2	400,000	50	200,000	0	–	40,000	40,000	240,000	200,000	440,000	2	13,200	453,200
12	Repair spalled portal concrete and replace stone facing	5	30,000	50	15,000	0	–	3,000	3,000	18,000	15,000	33,000	3	2,010	35,010
13	Remove existing concrete tunnel ceiling	6	8,000,000	65	5,200,000	0	–	800,000	800,000	6,000,000	2,800,000	8,800,000	3	535,920	9,335,920
14	Install manual fire alarm boxes	1	235,000	60	141,000	0	–	23,500	23,500	164,500	94,000	258,500	3	15,743	274,243
15	Increase tunnel daytime light level	3	502,000	50	251,000	0	–	50,200	50,200	301,200	251,000	552,200	3	33,629	585,829
16	Install flood gates	6	8,000,000	50	4,000,000	100	4,000,000	320,000	4,320,000	4,320,000	4,000,000	8,320,000	4	771,489	9,091,489
17	Install new CCTV cameras and system	6	220,000	50	110,000	100	110,000	11,000	121,000	121,000	110,000	231,000	4	21,420	252,420

(continued on next page)

Table D-13. (Continued).

User-Defined Priority	Preservation Action	Tunnel #	Capital Cost ($)	% Labor (0 to 100)	Labor Cost ($)	% Agency Labor (0 to 100)	Agency Labor Cost ($)	Agency Oversight Cost ($)	Total Agency Labor Cost ($)	Total Labor Cost with Agency Oversight ($)	Materials Cost ($)	Subtotal Cost ($)	Funding Year (1+)	Escalation ($)	Total Cost ($)
18	Install new LED lights	1	3,400,000	30	1,020,000	0	–	340,000	340,000	1,360,000	2,380,000	3,740,000	4	346,799	4,086,799
19	Replace fan #3 drive system	4	75,000	50	37,500	0	–	7,500	7,500	45,000	37,500	82,500	5	10,354	92,854
20	Install over-height truck detection equipment and system, remove existing	6	170,000	50	85,000	0	–	17,000	17,000	102,000	85,000	187,000	5	23,470	210,470
21	Remove and replace delaminated tile	2	170,000	75	127,500	0	–	17,000	17,000	144,500	42,500	187,000	5	23,470	210,470
22	Groundwater drainage relief hole installation	1	1,596,000	70	1,117,200	0	–	159,600	159,600	1,276,800	478,800	1,755,600	5	220,343	1,975,943
23	Replace existing trench drains	1	270,000	60	162,000	0	–	27,000	27,000	189,000	108,000	297,000	5	37,276	334,276
24	Remove and replace delaminated tile (walls)	3	78,000	75	58,500	0	–	7,800	7,800	66,300	19,500	85,800	5	10,769	96,569

25	Remove and replace delaminated wall tiles	5	20,000	75	15,000	0	–	2,000	2,000	17,000	5,000	22,000	5	2,761	24,761
26	Install transient voltage surge suppressors	4	24,000	50	12,000	0	–	2,400	2,400	14,400	12,000	26,400	5	3,313	29,713
27	Black hole effect – apply industrial coating to portals	1	120,000	70	84,000	0	–	12,000	12,000	96,000	36,000	132,000	5	16,567	148,567
28	Repair spalls on arch and walls	6	1,000,000	75	750,000	0	–	100,000	100,000	850,000	250,000	1,100,000	5	138,060	1,238,060
29	Install oil–water separator	6	90,000	50	45,000	0	–	9,000	9,000	54,000	45,000	99,000	5	12,425	111,425
30	Replace fluorescent lights in electrical room	5	30,000	70	21,000	100	21,000	1,200	22,200	22,200	9,000	31,200	5	3,916	35,116
31	Repair spalled concrete tunnel barriers	6	700,000	75	525,000	0	–	70,000	70,000	595,000	175,000	770,000	5	96,642	866,642
32	Replace expansion joint material in two locations	4	5,000	70	3,500	100	3,500	200	3,700	3,700	1,500	5,200	5	653	5,853

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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