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GUIDE FOR THE PRESERVATION OF HIGHWAY TUNNEL SYSTEMS

FINAL REPORT

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ABSTRACT

A Guide for the Preservation of Highway Tunnel Systems is the outcome of research on tunnel asset preservation included in this report, which addresses the tunnel management process from establishing agency goals and identifying tunnel preservation actions to prioritizing tunnel improvements and evaluating funding and staffing scenarios. It includes a metric to evaluate alternative preservation actions and to prioritize them based on an overall Measure of Effectiveness (MOE) Score. The MOE Score is a combination of three individual scores: Level of Service (LOS), Cost Effectiveness, and Risk-Based Urgency. Thirty-two sample preservation actions were utilized to develop, test, and calibrate the metric. A comprehensive catalog of preservation actions was also developed, encompassing many systems associated with tunnels and a variety of improvement projects. Once the preservation actions are prioritized, funding and staffing scenarios can be evaluated, allowing agencies to prepare a tunnel preservation plan to fit their funding limits and overall goals.

The outcome of this research also provides guidance on selecting agency goals and objectives and identifying performance measures for tunnels to monitor the impacts of the preservation actions on agency LOS.

Summary

Tunnel owners today are faced with aging tunnel assets and increasingly limited funding for the maintenance and preservation of their tunnels and associated systems. Prioritizing maintenance and preservation implementation is complicated, especially considering the complex systems comprising tunnels and that tunnel preservation often competes with other transportation elements, such as bridges and pavement, for available funding. In addition, several owners' maintenance staff knowledgeable about the tunnel systems are nearing retirement, leaving a new regime of inexperienced staff with minimal documentation regarding what is needed to maintain and improve their tunnels at a critical time when tunnel asset management is being promoted at the federal and agency levels. The research provided in this report develops a guidance document for tunnel asset management, for possible adoption by AASHTO and outlines the development of preservation actions and the use of a simple metric to evaluate and prioritize needed improvements. Once the improvements are prioritized, funding and staffing levels can be established for use in the capital planning process.

A review of recent related research, including several NCHRP reports and asset management guides, was performed and is documented in this report. In addition, interviews were conducted with six tunnel owners as part of this research. The interviews concluded that very few tunnel owners are using a formalized asset management approach for maintaining and preserving their tunnels. The interviewed tunnel owners are integrating asset management concepts by prioritizing needs based on safety, preservation, or other considerations, but the majority of them do not have a formalized prioritization approach for achieving the most value from available funding. It is expected that this is the norm for other tunnel owners across the U.S. Tunnel owners currently consider several factors when prioritizing preservation actions: safety (key factor) for the traveling public, system element condition, reliability to keep the tunnel open, traffic volumes, initial cost of the preservation action, and life-cycle costs. Current practice, however, is often reactive based on current condition and funding, instead of proactive from a formalized asset management approach.

The majority of tunnel owners interviewed stated that a formalized asset management approach that was simple to implement and considered levels of service (their goals and objectives), their specific tunnel conditions (i.e., good, fair, poor, severe), and traffic characteristics (urban, rural, or mix) would be valuable to them.

This report includes a metric that can be used to help tunnel owners prioritize and program their tunnel preservation actions. The metric utilizes a combination of several key scores to develop an overall measure of effectiveness (MOE). Tunnel owners create a listing of improvements and maintenance actions within each tunnel. Initial (capital) costs and applicable changes in cost, such as savings due to reduced maintenance or energy usage, are developed. In addition, an estimate of the risk-based urgency of the preservation action is made, considering the remaining life and current condition of the asset. Using this information, three MOE Scores are used to compute the overall MOE:

- Levels of Service (LOS) Score: This score reflects how well the proposed improvement meets the overarching goals and objectives of the agency.
- Cost Effectiveness (CE) Score: This score considers cost/user and is based on an annual cost over the theoretical remaining life of the asset, which effectively normalizes all preservation actions to facilitate comparison on a common basis. The number of users is based on Average Daily Traffic

(ADT) since this is a performance measure that is typically collected. By including the number of users, this score provides a means of emphasizing improvements in heavily utilized tunnels.

- Risk-Based Urgency (RBU) Score: This score is determined by considering the condition of the asset and its remaining life and by entering a rating after considering these factors. A high score means that the preservation action is urgently needed.

A risk-based asset management plan prioritizes improvements that pose the greatest risk if they are not implemented. With the proposed approach, the risk associated with not performing a preservation action is inherent in the agency's LOS Score and RBU Score. The LOS Score evaluates the impact of the improvement on safety, assuming it is selected as one of the key LOS for the agency, and the RBU Score evaluates remaining life, condition, and risk of unplanned events. Therefore, this approach will give higher priority to the preservation actions that present the highest risk.

Prioritization can be easily performed using the metric. The three scores are combined into one aggregate MOE Score for the preservation action, by weighting each score according to the agency's priorities. For example, if low cost is most important, the weight for this score would be higher than for the other two. Similarly, if the RBU, condition of the asset, and the potential for failure is of greatest concern, the weight for this measure would be increased. The combined MOE Score provides a means of comparing tunnel preservation actions, regardless of the tunnel system to which it is applied, the cost, or whether the tunnel is in an urban or rural area. It can provide the framework for developing the agency's 5-, 6-, or 10-year tunnel improvement program, and would be valuable to current tunnel owners and to those with inexperienced staff entering the work force.

The approach documented in *A Guide for the Preservation of Highway Tunnel Systems*, the result of this research, allows tunnel owners to not only establish priorities, but also to use the priorities to establish annual funding needs and agency staffing needs. Once the priority is established, agencies can use their discretion to establish the final sequencing of the implementation, and accordingly, the funding needed each year until all preservation actions have been implemented. Staffing needs can be easily assessed using the listing of improvement projects to be implemented each year. Thus, this approach affords an agency a means to plan their tunnel-related work for the foreseeable future.

CHAPTER 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. They are often critical links within the transportation system for a region; without them, the remaining roadways would be overburdened, and travel would be longer and less direct. Maintaining these assets in a state of good repair is paramount to maintaining the viability of the overall transportation network. This maintenance must be planned and, more importantly, budgeted for by tunnel owners.

As with the nation's other infrastructure, funding for highway tunnel improvements and maintenance is very limited; multiple agencies compete for available funding and multiple departments within an agency often compete for this funding. Overall, available funding is inadequate to meet the current needs to maintain and preserve the infrastructure. Identifying the specific improvements and maintenance needed and planning for these as future expenditures is critical. Prioritizing the needs is also a problem. Tunnels are only one part of the overall asset inventory for a transportation agency. Tunnel needs must be weighed against the other asset preservation needs and priority given based on the goals and objectives of the entire agency.

Most U.S. tunnels are aging. There are approximately 225 highway tunnels in the U.S. over 300 feet in length greater than 50 years old, and 128 highway tunnels over 70 years in age, as shown in Table 1.(1) and (2) Because each owning agency has relatively fewer tunnels than bridges, which number in the hundreds or thousands for many agencies, the person responsible for maintaining these tunnels is very familiar with their needs. These individuals know what needs to be done to keep the tunnel functioning and safe. But, just as existing tunnels are aging, the staff maintaining these tunnels is also aging, with about 50 percent of owners' personnel eligible to retire in the next 10 years.(3) As current staff members transition into retirement, incoming and less experienced staff will benefit from documentation of tunnel preservation actions and assistance in decision making regarding tunnel maintenance and improvements.

Table 1. Summary of Highway Tunnel Ages

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

SUMMARY OF HIGHWAY TUNNEL AGES		
Tunnel Age	**Year Constructed**	**Number of Tunnels***
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

*In 2003, FHWA 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 the above inventory that are less than 300 feet in length.

1.1 Goal for this Research Project

The goal for this research project is to develop a guidance document (i.e., *A Guide for the Preservation of Highway Tunnel Systems*) for adoption by The American Association of State Highway and Transportation Officials (AASHTO) to aid in the development of a tunnel asset management plan. The Guide (1) outlines how to develop a comprehensive list of preservation actions; (2) quantifies the benefits of tunnel preservation actions; (3) provides decision-making tools to optimize tunnel preservation actions; and (4) develops a method to determine appropriate levels of funding and staffing to achieve agency-selected goals. The guidance document developed through this research is applicable to the preservation of existing tunnels and to preservation planning during the design of new tunnels in both urban and rural areas.

To develop an asset management strategy for tunnels, current practices were investigated. A literature search was performed to investigate documented asset management strategies, and interviews were conducted with six agencies regarding their tunnel asset management practices. Guidance documents on asset management by AASHTO, NCHRP, and by an international group in New Zealand and Australia were reviewed. In addition, multiple NCHRP reports were researched for topics such as developing levels of service (LOS), performance measures and targets, resource allocation, and communicating the value of preservation. The goal of the literature search and agency interviews was to develop the methodology for tunnel asset management.

The scope of this research encompassed the development of a tunnel management framework. The major elements ultimately included were:

- Discussion of agency LOS
- Development of a list of potential tunnel performance measures
- Discussion on developing a list of preservation actions
- Development of a catalog of sample tunnel preservation actions
- Development of a metric that considers LOS, life-cycle costs, and RBU to prioritize improvements
- Use of the metric to evaluate agency funding and staffing needs.

The approach used is more fully documented in Chapter 2.

CHAPTER 2

Research Approach

The success of the final outcome of this research, *A Guide for the Preservation of Highway Tunnel Systems*, is contingent on its practical use, its flexibility for use by agencies with varying organizational and funding structures, and its ability to address the key factors that are weighed when establishing tunnel priorities. There is considerable documentation available on developing an asset management framework and on establishing agency LOS and performance measures. This information was considered in the development of the tunnel management strategy outlined herein. In addition, and to a much larger degree, the interviews with tunnel agency personnel and the experience of the research team with tunnel inspection, maintenance, rehabilitation and asset management drove the development of the metric included in this Guide. This experience allowed the team to develop a varied list of tunnel preservation actions to "test" the metric throughout its development.

2.1 Review of Tunnel Asset Management Strategies

To evaluate current practices and methodologies related to asset management, a review of existing technical literature, pertinent international and domestic scans, and NCHRP research projects was performed. In addition, interviews with owners were conducted during the initial phase of the project to document industry practices related to tunnel operation, maintenance, and asset management approaches to preservation actions. Six tunnel owners in the U.S. were interviewed: CDOT, Caltrans, MassDOT, PANYNJ, VDOT, and WSDOT.

2.2 Catalog of Preservation Actions

A required element of this research was the development of a catalog of sample preservation actions. The research team utilized the experience of key personnel who had performed multiple tunnel inspections and life safety analyses, provided oversight for tunnel maintenance, and designed rehabilitation of tunnels and tunnel systems. Each tunnel system and its associated equipment and/or elements were listed. From this, a list of potential preservation actions was developed. This catalog provides a fairly comprehensive listing that is applicable to the majority of tunnels in the U.S.

2.3 Metric for Evaluating Priorities

Guidance in prioritizing preservation actions is desperately needed by tunnel owners across the country. Procedures for evaluating alternatives and selecting the level of priority vary from agency to agency. Most agencies utilize the results of inspections and the priorities established by the inspection team to guide their selections, but evaluating mechanical and electrical system requirements against structural improvements is challenging, and comparing tunnel preservation actions against the agency's bridge, pavement and other asset requirements further adds to the complexity. Along with this, many knowledgeable and experienced tunnel owners and operators are nearing retirement, making it evident that a documented process is needed. A metric to evaluate and prioritize alternative preservation actions for any tunnel system will benefit tunnel owners and provide a consistent platform to be used as personnel change within agencies.

To develop the metric to be included in the Guide, the key criteria for making decisions regarding tunnel preservation actions were listed. These criteria include:

- Agency levels of service/goals and objectives
- Initial cost/life-cycle cost
- Daily traffic
- Remaining life
- Condition
- Risk of unplanned events (flood, earthquake, fire, etc.)
- Regulatory requirements
- Improvement/impact on life safety

Ultimately one single measure of effectiveness (MOE) is needed to facilitate comparison between alternative preservation actions. Intuitively, all of the factors above could be combined by multiplying values to maximize a desirable high rating, and dividing by values for factors that, when low, produce a more favorable result. For example, low life-cycle costs are preferable to high life-cycle costs. Therefore, this factor would be applied in the denominator such that lower life-cycle costs would return a higher MOE. Similarly, the higher the risk, the greater the need for the improvement. Therefore, the risk rating would be applied to the numerator. This method is possible, but with such a wide range of values for each criterion, it would be difficult to assess its viability.

A means of subdividing the criteria into key components was needed. The factors were grouped into three key element areas: Agency LOS, Cost, and Condition/Urgency. Factors were assigned to each of these areas and ultimately resulted in the three scores that are combined to obtain the overall MOE:

- Level of Service (LOS) Score
- Cost Effectiveness (CE) Score
- Risk–Based Urgency (RBU) Score

Underlying this scoring methodology is the Analytical Hierarchy Process (AHP). AHP is an accepted technique for evaluating complex problems with multiple alternatives by breaking them into a hierarchy of smaller problems that can be evaluated more readily. The alternatives can be compared at the sub-problem level, providing an opportunity to evaluate them in a rational way on that basis, and can also be combined ultimately to provide an overall means of comparison.

To evaluate the viability of the metric, a listing of diverse preservation actions was developed, incorporating sample improvements for multiple systems associated with a tunnel. The scoring methodology was developed for each of the three sub-scores, and then combined into an overall MOE to be used for prioritization. To combine them, the three scores had to be of similar magnitude. Each score was, therefore, developed in a manner that resulted in a score of 0 to 100. To accomplish this, the CE Score incorporated a factor that provided dispersion of the data between 0 and 100. The scoring was tested using the sample projects that were used as the test population.

For the metric to be successful, it must not only provide reasonable, rational results, but must also have the flexibility for agencies to adjust based on the relative significance of their goals, of the three factors (LOS, cost, risk-based urgency), and ultimately, how they contract their work. Therefore, considerable flexibility was built into the process. Initially, the LOS Score is determined based on how well the preservation action affects the particular LOS. The agency has the ability to adjust the relative weights of the LOS, thereby emphasizing certain goals over others. For example, safety and preservation may be weighted much higher than quality of service and environment. Similarly, when combining the three scores to obtain the overall MOE, the agency is allowed to weight one factor higher than the others. If they are focused on improving life safety systems within the tunnel, for example, they may weigh the RBU Score higher than the CE Score. Ultimately, the prioritization that results from the use of the metric can be adjusted to reflect the agency's tunnel traffic characteristics and contracting methods, to allow work to proceed in one tunnel at a time or by system, across the entire network of tunnels. In this way, the metric provides a rational tool for prioritization with built-in flexibility for owners to adjust to reflect their organization, concerns, and operational requirements.

The methodology developed for determining the overall MOE is documented in *A Guide for the Preservation of Highway Tunnel Systems*. The methodology is detailed in the next chapter, Chapter 3, Findings and Applications.

2.4 Funding and Staffing

Using the same sample data, agency funding and staffing scenarios were evaluated. Initial costs for preservation actions used to evaluate cost effectiveness were further analyzed to develop contractor total costs and agency labor costs. With the priority of preservation actions established, it is possible to identify the improvements that "fit" within a prescribed budget (top-down approach), or alternatively, to establish a capital plan based on implementation of an identified grouping of preservation actions for each year (bottom-up approach).

Staffing needs can be developed in a similar manner. Using the agency labor costs and average wage rates for agency employees, a rough order of magnitude staffing can be determined for the improvements assigned to each year, whether using the top-down or bottom-up approach.

Once the preservation actions are implemented, the impact of the improvement can be evaluated using the pre-established performance measures. The performance measures allow the agency to monitor how well the implementation of asset management is improving the LOS. Thus, the tunnel asset management process is a cyclical process that can be repeated based on monitoring results.

Detailed examples of the use of the metric for prioritization, and for funding and staffing evaluations are provided in Chapter 3, Findings and Applications.

CHAPTER 3

Findings and Applications

The need for planned, proactive asset management for transportation infrastructure has been recognized for decades. Substantial progress has been made in this regard for bridges and pavement, however, tunnels are complex assets with mechanical and electrical systems and asset management practices for tunnels have therefore lagged. To understand the current strategies for tunnel asset management, this research began with a literature review and agency interviews. Information gained from these investigations were considered when developing the methodology for evaluating and prioritizing preservation actions contained herein, and in the development of the approach for funding and staffing scenarios. This chapter documents the results of the research, including the investigation of current practices, and the use of a metric to evaluate and prioritize preservation actions, and to plan for funding and staffing scenarios.

3.1 Review of Tunnel Asset Management Strategies

To evaluate current practices related to tunnel asset management, a review of existing technical literature, pertinent international and domestic scans, and NCHRP research was performed. The literature search and agency reviews provided useful information for developing an asset management framework. In addition to the literature review, interviews were conducted with agency personnel for six tunnel owners to document industry practices related to tunnel asset management. A summary of these investigations is provided below.

3.1.1 Technical Literature and NCHRP Research Projects

Over the past two decades, the principles and practice of asset management have evolved to focus on data-driven maintenance and preservation and improvement decisions that reflect life-cycle costs and the priorities of the agency. The technical literature supporting these efforts includes guides and NCHRP studies, papers, and reports as briefly reviewed below.

Numerous research projects have been completed over the last several years providing guidance and tools for transportation asset management. Much of the previous work has resulted in proposed methodologies for large system-wide assets, i.e., bridges and pavements, encompassing hundreds of thousands of pavement miles and thousands of bridge structures. Although the number of highway tunnels greater than 300 feet in length in the U.S. is currently about 362 [(1) and (2)], they are still critical to the performance of the roadway system that links them to the overall transportation network. Moreover, maintaining the tunnels in good condition is an objective of every tunnel owner.

It is well established that there are limited dollars available for transportation agencies to maintain their highway assets in good condition. AASHTO recognized this in 2002 when it created the *Transportation Asset Management Guide.* AASHTO's guide was developed to assist transportation owners by presenting tools for evaluating return on investment and improving economic efficiency, resource allocation, and budgeting decisions. It defines asset management as: *Transportation Asset Management is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively* *throughout their life-cycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives.*[4] This asset management process is also applicable to maintaining highway tunnels as a functional part of the highway system.

Research was conducted in 2002-2003 to inventory the number, age, and characteristics of highway tunnels in the U.S. as a pre-requisite for the development of the 2005 Federal Highway Administration (FHWA) ***Highway and Rail Transit Tunnel Inspection Manual***.[5] Table 1 in Chapter 1 shows the number of tunnels inventoried at that time, with their updated age in years and as supplemented by NCHRP Project 20-68A Scan 09-05, Appendix E, ***Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection and Operations***, April 2011.[1 and 2] As evidenced in Table 1, a majority of highway tunnels inventoried in 2003 and supplemented in 2011 exceed 50 years in age. As a result, many tunnel owners are undertaking major repairs, rehabilitation, and replacement of their tunnel assets.

FHWA recognized the need for preservation of the older existing highway tunnels in early 2002 and also initiated the development of the ***2005 Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual.***[6] This manual provides chapters on a) the systems comprising a tunnel including the structure, ventilation systems, lighting systems, and other systems/appurtenances; b) guidance for preventive maintenance of tunnel structural, mechanical, electrical, and lighting systems; and c) rehabilitation of structural elements. It also includes a life-cycle cost analysis methodology for tunnel owners to follow when making preservation action decisions. Subsequent to the 2005 manuals, the FHWA updated and incorporated them in the 2015 FHWA ***Tunnel Operations, Maintenance, Inspection and Evaluation*** **(TOMIE)** ***Manual.***[7]

Many transportation agencies are currently using performance-based approaches to planning/ programming, monitoring system performance, and developing integrated data and analysis tools for evaluating operations and preservation activities. Due to financial constraints imposed upon these agencies, a systematic approach using asset management principles is critical to making informed, cost-effective decisions regarding their assets. AASHTO's 2002 ***Transportation Asset Management Guide*** provided such a framework, as shown in Figure 1.[4]

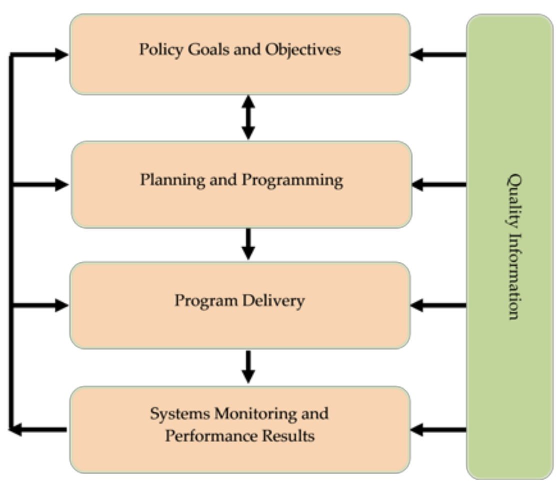

Figure 1. Asset Management Framework from the AASHTO Transportation Asset Management Guide, 2002

The framework in Figure 1 is outlined as follows:

- Policy Goals and Objectives: These goals and objectives will address applicable LOS standards to be achieved by the agency, such as reliability, safety, security, quality of service, and preservation. Once the LOS standards are identified, the agency should set performance measures to provide a means of evaluating how well the LOS standards are being met. The performance measures typically relate to categories such as social, economic, environmental, and preservation (operations and maintenance) actions.

- Planning and Programming: Plans and programs for preservation actions are developed once performance targets are set. The owner should consider life-cycle costing analysis and risk-based issues while developing the plans and programs.
- Program Delivery: The necessary repair, rehabilitation, or replacement (based upon an evaluation of alternatives) is performed.
- System Monitoring and Performance Results: The agency should monitor the results of the work performed through periodic gathering of data from inspections to ensure results are achieved.

While a comprehensive literature review was conducted to support this research, a summary of findings is provided below for general introduction and background purposes. For the complete literature review, refer to Appendix A of this document.

The 2011 *AASHTO Transportation Asset Management Guide - A Focus on Implementation*[8] provides key information for assisting agencies in understanding and implementing an asset management program. The framework for asset management was further advanced in **NCHRP Project 20-74 *An Asset-Management Framework for the Interstate Highway System* (NCHRP Report 632).[9]** The objectives of this research were to provide a method that was holistic, provided a basis for making decisions that were cost effective and beneficial, and easy to implement. Report 632 expanded upon the framework from the 2002 AASHTO *Transportation Asset Management Guide* by addressing the concepts of risk management, conditions of assets, tools for asset management, implementation guidance, and by encouraging a performance-based approach.

To establish the framework for asset management, an owner must first define the expectations for LOS. **NCHRP Project 20-74A *Development of Levels of Service for Interstate Highway System* (NCHRP Report 677) [10]** defines LOS as follows:

> *In the context of asset management, this term is synonymous with service level. Although there is the potential of confusion with the identical term used in traffic studies (i.e., traffic LOSs), highway maintenance agencies have been using the term "level of service" for many years to describe the condition of roadway and roadside assets and the quality of maintenance services. Although "level of service" and "service level" can be used interchangeably, "level of service" will be used throughout this report. The term is nearly synonymous with performance measure, but there is a subtle difference in usage. In practice, LOS is used to characterize the performance measure by assignment of a letter grade or score to a specific performance measure or range of measures.*

Once LOS are defined by the owner, the next step in the asset management process is to identify performance measures and targets for the various asset classes. Both NCHRP Reports 551 and 706 present research for identifying these performance measures. **NCHRP Project 20-60 *Performance Measures and Targets for Transportation Asset Management* (NCHRP Report 551)[11]** had the research objectives to investigate performance measures suitable to asset management and to develop a framework for establishing performance measures and setting targets for use in asset management.

NCHRP Project 20-57 *Analytical Tools for Asset Management* (NCHRP Report 545)[12] was undertaken to provide new analytical tools to support asset management. It was developed to assist agencies in making difficult tradeoff decisions for resource allocations while considering asset preservation concerns. The outcome of Phase I of this research was the development of AssetManager

NT and AssetManager PT. AssetManager NT is a tool to assist transportation agencies in understanding how different patterns of investment in transportation assets will affect long-term performance of the system. It does not include analytical capabilities typically found in individual asset-specific management systems, such as deterioration modeling, simulation, strategy selection, or optimization. The framework presented in Report 545 illustrates how tunnel asset management data can be used to support tradeoff decisions.

NCHRP Project 08-70 ***Uses of Risk Management and Data Management to Support Target-Setting for Performance-Based Resource Allocation by Transportation Agencies*** **(NCHRP Report 706)[13]** was developed in two parts. Part 1 discusses applications of risk management to support performance-based allocation. Part 2 provides the basis for using information technology tools and data management practices to support data sharing and integration in transportation agencies. Eight DOTs were interviewed and the results as to how they were incorporating information technology into management of their assets were presented.

As systems and infrastructure in a tunnel ages, it is essential that life-cycle costing analysis of systems being considered for repair, rehabilitation, or replacement to be included in the evaluation of alternatives for prioritization. A few of the research items present similar methodologies to assist managers in transportation agencies in making informed decisions. **NCHRP Project 08-71** ***Estimating Life Expectancies of Highway Assets, Volumes 1 and 2*** **(NCHRP Report 713)[14]** addresses this concept in detail. Volume 1 establishes how to plan and design for life expectancy models, and how certain states have done this for statewide assets (bridges, pavements, signs, guide rails, etc.). The report also presents several different models, including life-cycle cost models, which could form a basis for life expectancy computations. Volume 2 describes the technical issues and data needs associated with estimating asset life expectancies and the practices used in a number of fields to make such estimates.

The objectives of **NCHRP Project 14-21** ***Resource Allocation Logic Framework to Meet Highway Asset Preservation*** **(NCHRP Report 736)[15]** were to describe, in useable terms, an analysis framework that DOT staff could use to allocate resources across principal categories of highway assets to ensure system preservation and to demonstrate the framework's application.

NCHRP Project 12-82 ***Developing Reliability-Based Bridge Inspection Practices*** **(NCHRP Report 782)[16]** establishes goals of developing reliability-based bridge inspection practices for (1) improving the safety and reliability of bridges and (2) optimizing resources for bridge inspection[14].

The ability to keep bridges open to traffic is paramount for an agency's transportation system to function as planned and designed. NCHRP 12-82 developed a reliability matrix to establish bridge inspection intervals. This same reliability concept proposed for bridge inspection is applicable to the inspection of tunnel elements, as indicated in the sample reliability matrix below:

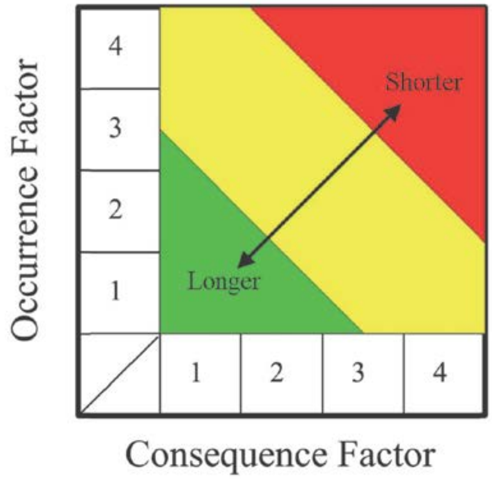

Figure 2. Reliability Matrix for Determining Maximum Inspection Intervals for Bridges

This conceived approach to bridge inspection provides a methodology to improve bridge safety and reliability by focusing inspection resources where they are most needed. It also provides for an optimized allocation of resources, as inspection requirements are better matched to inspection needs through a reliability-based assessment.

In **NCHRP Project 14-24** ***Communicating the Value of Preservation: A Playbook (NCHRP Report 742)***[17] the main objective was to develop guidance that state DOTs and other transportation agencies could use to formulate and implement strategies for communicating the role and importance of maintenance and asset preservation in sustaining highway system performance. It also provides creative ideas for setting up an agency's preservation campaign.

The ***International Infrastructure Management Manual*** published by the National Asset Management Support Group in New Zealand and Australia, 2011[18] builds upon previous research and actions implemented by numerous transportation agencies and incorporates them into the manual. It provides numerous examples to aid transportation agencies to utilize asset management for their transportation facilities and includes several case studies.

Two other references pertinent for this project are the tunnel scans conducted in Europe in 2005 and in the U.S. in 2009. ***Underground Transportation Systems in Europe: Safety, Operations and Emergency Response***[19] is the report produced from a scan of European tunnels by 11 personnel from the U.S. who traveled to Denmark, France, Norway, Sweden, and Switzerland in 2005. The objectives of the scan were to learn what is being done internationally for underground transportation systems in the areas of safety, operations, and emergency response. The scan focused on equipment, systems, and procedures incorporated into modern underground and underwater tunnels by leading international engineers and designers.

NCHRP Project 20-68A (Scan 09-05) ***Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection, and Operations***[2] was a scan of U.S. tunnels; the report offers significant background information that can be used in the tunnel preservation guide to be produced as part of this research. This scan included nine members, five of whom were from domestic DOTs who visited tunnel owners as part of the scan. Key observations taken from the scan include:

- Tunnels with functional systems such as ventilation, fire suppression, and electrical and mechanical components are complex structures with more intensive needs for maintenance and operation than traditional transportation facilities.
- A proactive operational financial plan that considers life-cycle costs must be developed to address the need for preventive maintenance, system upgrades/replacements, and operator training and retention.
- Funding for tunnels should not only include buying replacement parts when the tunnel is built, but should also include buying replacement parts that may not be available over time due to obsolescence or other reasons.
- A separate fund should be dedicated to tunnels, and agencies should work with local funding, planning, and maintenance organizations to establish the fund.

The tunnel owners stated that their regularly encountered maintenance issues attributable to age are defective and obsolete tunnel mechanical and electrical system elements and difficulty finding replacement parts for the original equipment. Other maintenance issues included:

- Controlling water leaks and other drainage issues
- Electrical system and wiring degradation
- Concrete deterioration and corrosion of embedded reinforcement
- Tile delamination
- Surface obstructions when washing walls
- Difficulty in cleaning light fixtures
- Cumbersome ventilation fan motor drive equipment and plenum dampers
- High maintenance needs for sensors for various monitoring equipment
- Keeping the air ducts free of dust accumulation
- The limited number of cycles that portal doors can withstand

The Report indicated that the financial management plan for tunnels should not only include initial costs for construction, but also should address future preservation and upgrade needs. The team found that without a dedicated fund, tunnel upgrades do not compete well with system-wide needs, such as traffic signals and pavement preservation.

National Fire Protection Association's **NFPA 502 *Standard for Road Tunnels, Bridges and Other Limited Access Highways* (2008 Edition)**[20] states the following as far as maintaining highway tunnels:

- Section 15.1.1: Fire protection, life safety, emergency ventilation, communication, traffic control, and electrical systems shall be inspected and tested for operational readiness and performance in accordance with the frequency requirements of the applicable NFPA standards or in accordance with 15.1.2.
- Section 15.1.2: Integrated and/or interconnected fire protection, life safety, and emergency systems shall be inspected and tested for operational readiness and performance in accordance with the frequency requirements established by the basis of design or intervals not to exceed five years.
- Under Annex A to NFPA 502: The power distribution system should be maintained through an approved annual maintenance program. The electrical distribution maintenance program should

be consistent with NFPA 70B Recommended Practice for Electrical Equipment Maintenance, 2010 Edition.

3.1.2 Industry Practices Research

To further evaluate current practices for tunnel preservation, six agencies were interviewed: CDOT, Caltrans, MassDOT, the PANYNJ, VDOT, and WSDOT. Eighteen questions were asked in four categories (General, Asset Management Strategy, Prioritization of Tunnel Preservation Actions, and Funding). The entire listing of responses to these questions are provided in Appendix B for each participating agency. A synopsis of the answers provided for the four categories of questions are as follows:

3.1.2.1 General

Tunnel owners were asked to characterize their tunnels and maintenance practices.

- Two owners have only urban tunnels; three owners have both urban and rural tunnels, with most being urban tunnels; and one owner has both with most being rural tunnels. Those with urban and rural tunnels indicated that the traffic characteristics of each affect their decisions regarding the prioritization and timing of the work to be done.
- Five tunnel owners use a combination of internal and external contracts to perform needed maintenance and improvements, with most maintenance performed by internal forces. External contracts are typically used for major maintenance projects. One tunnel owner uses all internal forces for tunnel maintenance and preservation.
- Five tunnel owners indicated they have to defer preventive maintenance or preservation actions due to funding limitations. One owner with a dedicated funding source through tolls is deferring maintenance not because of funding, but because of current staffing limitations.
- All tunnel owners interviewed indicated that they phase repairs and rehabilitation over multiple years; one tunnel owner stressed that structural issues are addressed in a timely manner.
- Capital plans for accomplishing required preservation actions for the owners are at 5-year (three owners), 6-year (one owner), and 10-year (one owner) intervals. One tunnel owner stated that prioritized repairs are made based on risk and not tied directly to a capital plan.
- All tunnel owners are experiencing increased costs due to aging systems in tunnels. The majority interviewed concurred that some formalized approach to asset management and prioritization of preservation actions would be helpful. One tunnel owner utilizes a Maintenance Management Information System (MMIS) already and another has studies underway to determine the best MMIS system to purchase for implementation within his agency’s tunnels.

3.1.2.2 Asset Management Strategy

While the responses provided varied greatly among the tunnel owners, the individuals interviewed were all aware of an overall asset management strategy for bridges and pavements, but not for tunnels.

- For overall asset management goals/objectives for their tunnels (i.e., LOS) as they relate to reliability, safety, security, quality of service, and preservation, most interviewed were not aware of the agency-level defined LOS. However, each of the owners related that safety and reliability are key objectives to their asset management strategy.
- To evaluate if LOS goals are being met for tunnels, performance measures must be established. When asked what performance measures they collect for tunnels, the interviewed agencies

indicated that they collect data on average daily traffic, number of accidents, and roadway surface conditions. A few collect other information such as performance of lighting, monitoring of noise, and conditions determined through inspections. MassDOT indicated that performance measures vary from how quickly the Department responds to incidences to how quickly they process invoices to contractors and all steps in between. In other words, they are measuring each step of their procedures to determine where efficiencies can be realized.

3.1.2.3 Prioritization of Tunnel Preservation Actions

- When asked what tools they use for tunnel improvement prioritization, Caltrans and CDOT use no tools, just staff expertise, to prioritize actions. MassDOT, VDOT, and WSDOT use a computerized maintenance management system for tracking maintenance functions, but prioritization is performed based on staff expertise. The PANYNJ has developed a transportation index, condition index, and an internal formula for prioritization.
- All the owners consider issues such as cost of repair, condition, usage/traffic, and risk/impact to the public when prioritizing repairs. However, the determined priority is not always followed, because grouping repairs to work within one tunnel at a time can be more economical. Some owners responded that they do, in fact, group the work. Most tunnel owners with urban tunnels indicated that they can't typically group the work because they can't close the tunnel for an extended period due to traffic considerations and lack of alternative routes. One tunnel owner with all urban tunnels indicated they follow the prioritization to whichever tunnel is affected, since they shut down lanes nightly to complete regular maintenance work.
- When asked what characteristics a prioritization tool should have, the tunnel owners expressed that user-friendly software such as an Excel Spreadsheet that can be used on desktop computers, wireless tablets, or iPhones, would be best. It is clear that the owners are not interested in complicated input or time-consuming programs for their relatively few tunnel assets.

3.1.2.4 Funding

- The funding distribution for tunnels varies for each agency. MassDOT tunnels are tolled and these tolls provide a dedicated funding source for tunnel maintenance and improvements. For the other agencies interviewed, tunnel funding is part of the bridge budget, and the portion that is directed to tunnels varies. For WSDOT, tunnels were considered a "miscellaneous asset" within the bridge program, similar to culverts, signs, etc. The available budgets for tunnels have been extremely limited because of their status within the bridge program. The other agencies apportioned the budget between bridges and tunnels, but the split varied from year to year depending on need. Where tunnels are part of the overall bridge program, the tunnel needs compete directly with the bridge needs for available funding.
- Staffing levels are relatively constant at most agencies. Tunnel owners consider their available staff, to some degree, in programming the needed improvements. The agencies indicated they usually have sufficient staff to perform maintenance, but use external consultants and specialty contractors as an extension of their staff when needed for specific preservation projects or major tunnel preservation projects. MassDOT and VDOT are currently performing studies to determine the work output levels of each employee to evaluate efficiency as part of a review of their overall staffing needs.
- To program their work into their specified capital plans, agencies rely on internal cost estimates prepared by staff. When consultants are hired to perform inspections and provide priorities and cost estimates, these costs are utilized for communicating budgetary needs for future years.

These interviews clearly indicate that tunnel owners would benefit from taking a more proactive approach to tunnel maintenance and that guidance on determining tunnel preservation needs and priorities would be helpful. The guidance, however, must be adaptable by tunnel agencies without causing undue overhead burden, and must be easily integrated into their workflows and procedures for tunnel owners to use it.

3.2 Asset Management Approach for Tunnels

The goal of this research is to develop guidance for tunnel owners to manage and preserve tunnel assets. An asset management approach for tunnels should be data driven, should include maintenance, preservation, and improvement decisions that reflect life-cycle costs and agency priorities. This research addresses these basic requirements and provides a simple to use metric to prioritize preservation actions, considering agency objectives, life-cycle costs, and the urgency for the improvement. The approach to tunnel asset management as provided below follows the framework presented from the 2002 *AASHTO Transportation Asset Management Guide*, beginning with the establishment of agency goals and objectives, followed by planning and programming the preservation actions. After the actions are implemented, the effectiveness of the preservation actions can be monitored through the use of established performance measures.

The following sections establish the framework for a tunnel asset management approach and provide a methodology for managing tunnel assets:

- Levels of Service - Selection of agency goals and objectives
- Performance Measures - Establishment of performance measures to evaluate the effectiveness of preservation actions
- Preservation Actions - Identification of needed tunnel preservation actions, through inspections and evaluations of applicable codes and standards
- Metrics to Analyze Effectiveness of Preservation Actions - Use of a simple methodology that considers impact on LOS, cost effectiveness, and risk to develop an overall MOE
- Prioritization - Use of the overall MOE to prioritize the identified preservation actions
- Monitoring - Use of performance measures to evaluate the effectiveness of preservation actions

3.3 Levels of Service

LOS capture the performance objectives of interest and relevance to the transportation agency using measures that relate to the needs of the agency. Many transportation agencies have already developed an overall asset management strategy and have established their LOS for the entire agency. These LOS should be used in developing the LOS Score outlined below. In the absence of established LOS standards for the agency, it is possible to develop LOS specifically for the agency's tunnel assets. The following LOS standards were selected for use in the metric examples provided herein. They are based on the review of the literature, the interviews with six tunnel agencies, and experience with several other U.S. tunnel owners. An Agency Asset Management Team (AAMT) should establish the LOS to be used in the metric based on the individual agency's specific needs. The team should include members from multiple disciplines including structural, electrical, mechanical, lighting, civil, and geotechnical.

- Reliability: The ability to keep the tunnel open to the traveling public.
- Safety: The tunnel and its systems are safe for the traveling public as well as for workers who perform maintenance and repairs.

- Security: The tunnel is secure from technological or natural hazards.
- Preservation: The condition and remaining life of the tunnel elements allow the tunnel to function well into the future.
- Quality of Service: The perception to the users of the tunnel for comfortable travel in terms of ride, visibility, aesthetics, and environment.
- Environment: The absence of negative impacts on the environment as a result of the tunnel and its systems.

3.4 Performance Measures

Performance measures are used to monitor the performance of the agency in meeting their goals and objectives (LOS). Performance measures should be established as an initial step in the asset management process. Specific performance measures should be selected for each LOS to measure the effectiveness of improvements designed to meet the agency's goals. When establishing performance measures, it is important to consider all tunnel systems and to allow for tracking changes in performance over time. For example, tunnel fans, lighting, CO detection, and CCTVs are all assets within a tunnel that are all comprised of different systems. Time between failures might be a performance measure for each that would reflect the performance of these systems. Time between failures after improvements are made compared to time between failures prior to the improvement can be used to capture the change in performance with respect to the LOS. When establishing performance measures, it is critical that they be measurable and include readily available data. The acronym SMARTER is commonly used to capture the attributes of the performance measures:[18]

- 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.
- Timebound: Reflects the time frame over which action is required.
- Evaluation: Continued assessment of the appropriateness of the measures and target.
- Reassess: Review of performance measures and targets on a regular basis.

One tunnel owner interviewed attempted to determine what performance measures are typically being used today; the responses indicate that not many performance measures are routinely captured. ADT and number of accidents were the only two performance measures that the respondents were aware of being collected on a regular basis. For each LOS, example performance measures are shown in Table 2. Please note that suggested performance measures in bold type are deemed most appropriate for most tunnel owners.

Table 2. Examples of Performance Measures

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 accidents on surrounding roadways per year 5. Bi-directional traffic 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) 7. General Ventilation: Percentage of time carbon monoxide (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(s) 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(s) is fully functional
Security	**1. Security Cameras: Percentage of time cameras are functioning** **2. Percentage of time over-height detection systems are functioning** 3. Hazardous materials 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 of fire emergencies and drills including a lessons learned review of each incident with participating agencies 8. Number of enforcement events or citations

EXAMPLES OF PERFORMANCE MEASURES	
Levels of Service	**Performance Measures**
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 heating, ventilation and air conditioning (HVAC) systems
Quality of Service	**1. No customer complaints** **2. Cleanliness** **3. Delay: Average peak hour delay** **4. Change in ADT** 5. Pavement international roughness index (IRI) 6. Number of closures, lane closures per year 7. Clearances, no obstructions 8. No ponding water on pavement 9. No missing tiles or less than X SF of missing tiles 10. No dislodged ceiling panels 11. Signage, message signs easily readable
Environment	**1. No damage to environment (spills)** 2. Oil water separator functioning as designed

3.5 Preservation Actions

Similar to AASHTO's adopted definition of bridge preservation(21), tunnel preservation includes actions or strategies that prevent, delay, or reduce deterioration of tunnels or tunnel systems; restores the function of existing tunnels; keeps tunnels and their systems in good condition; and extends their life. Tunnel preservation may also include preventive maintenance [cyclical preventive maintenance (activities on a pre-determined interval) and condition-based preventive maintenance] and rehabilitation as defined below.

The 2011 FHWA *Bridge Preservation Guide*(21) provides definitions of preservation actions for bridges, which can also be extrapolated for tunnel preservation. Preservation actions include both preventive maintenance and rehabilitation activities, as follows:

<u>Preventive Maintenance</u>: 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 system (without substantially increasing structural capacity). Preventive maintenance includes cyclical (non-condition based) and condition-based activities.

- Cyclical (Non-Condition Based) Preventive Maintenance: Activities performed on a pre-determined 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, etc.).

- Condition-Based Preventive Maintenance Activities: Activities that are performed on tunnel elements as needed and identified through the tunnel inspection process. These activities are typically performed on a tunnel in overall good to fair condition to restore tunnel elements to a state of good repair. Similar to cyclical preventive maintenance activities, the condition-based preventive maintenance activities are designed to extend the tunnel's useful life. These may include emergency or other unscheduled, time-sensitive maintenance or repair activities.

Rehabilitation: Rehabilitation involves major work that is 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, or the addition of new tunnel systems as a result of a fire life safety assessment.

A list of preservation actions for several different systems are provided in the Catalog of Preservation Actions in Appendix C.

3.5.1 Identifying Preservation Actions

Departments of Transportation and other highway authorities expend considerable funds inspecting and evaluating their tunnel assets. The National Tunnel Inspection Standards (NTIS) require regular inspections of tunnel assets. Inspections may be performed by agency personnel or outside consultants as walk-through, periodic, or in-depth inspections. In-depth inspections and tunnel evaluations provide the best mechanism for establishing tunnel preservation actions. Tunnel preservation actions may also be identified by:

- Tunnel operations personnel when a piece of equipment malfunctions;
- Specialty companies when providing troubleshooting and testing of equipment or systems;
- Agency/consultant after performing code evaluations to identify actions needed to comply with current codes and standards; and
- Operational needs.

Following these inspections and evaluations, a listing of potential improvements can be made. The tunnel, affected systems and elements, and each specific problem or issue should be documented. The life-cycle cost for the improvements, as well as the service life and remaining life of the existing asset, and its condition, are also assessed. This data is captured during the identification of preservation actions for future use when implementing the metric.

3.6 Metrics to Analyze Effectiveness of Preservation Actions

As indicated by the agencies interviewed for this research, tunnel maintenance and improvements are typically planned and included in the transportation agency's 5-, 6-, or 10-year Capital Plans due to growing needs of the transportation agencies, with limited available funding to meet these needs. A metric or means to evaluate and prioritize each improvement is necessary to develop the long-term program.

Specific actions, whether for a tunnel element, tunnel system, or the tunnel overall, will result in improvements in the performance of the component and the tunnel in terms of:

- Improving the performance of the tunnel relative to the agency specific goals and objectives (LOS).

- Changing the maintenance and operating costs for the agency.
- Changing the performance to benefit the users' experience.
- Changing the remaining life of the component or the tunnel.

Metrics to analyze the effectiveness of each preservation action must be simple enough to be easily applied and understood, have the data available to support the measures, and be sufficiently realistic to capture the changes in performance of the tunnel or tunnel system. While many tunnel owners and operators know and understand how the tunnel performance changes with investments in maintenance and improvements, a metric that measures the effectiveness, or MOE, can validate their decisions and serve as a communication and training tool. As a communication tool, the MOE serves to allow other parts of a large organization to understand the role the tunnel plays in the transportation system. Whether the decision makers are politically or technically motivated, the MOE must address this need. The MOE also serves as a training tool, recognizing the need to train the next generation of tunnel operators given the aging workforce.[(3)]

To ultimately prioritize maintenance actions, it is important to first develop LOS standards, assess life-cycle costs, assess the urgency of the action in terms of the remaining life and current condition, and compute an overall MOE. This section describes how these measures are developed for tunnels and how they are assembled into a score using a simple metric, which can be used to compare and prioritize maintenance actions. In each case, three measures, or scores, are developed and normalized so that the measures are on a consistent scale of 0 to 100, and then combined to provide an aggregate MOE Score. It is this MOE that is used to establish priorities.

The three scores that are outlined below are LOS Score, CE Score, and RBU Score. These scores address all of the factors considered in assessing tunnel priorities. The sub-sections below focus on each of the scores followed by the calculation of the overall MOE Score, which is ultimately used for prioritization and funding and staffing evaluations.

The benefit of using the metric is in its reliance on actual data and the use of a standardized approach to rate and compare preservation actions. The metric outlined below has built-in flexibility to allow an agency to place greater emphasis on certain LOS and to adjust the resulting priorities based on their program delivery preferences. The resulting prioritization is data driven and the process can be repeated each year or when new inspection or evaluation data is available.

A list of 32 preservation actions in six different tunnels, including rural and urban locations, was created to facilitate the metric development. This mock-agency exercise allowed the research team to use, adjust, and identify areas requiring flexibility. It also allowed the metric to be calibrated for multiple user input and interpretation. The final result of this exercise is presented in Appendix D of the Guide; a sample set of data is presented in the following sub-sections of this report.

3.6.1 Development of the Agency LOS Score

To evaluate the effectiveness of a proposed tunnel preservation action, several factors must be considered. One of the major factors is the effect the improvement has on achieving the agency's goals and objectives (i.e., meeting their LOS standards). A LOS Score is needed to evaluate this component of the overall effectiveness of the action.

There are various ways to evaluate the effect of an improvement on LOS. One way to quantify how well a preservation action improves the service level is to simply provide a rating (i.e., 1 to 100) as a qualitative assessment of performance. Alternatively, the rating can be based on ranges of values. For example, a rating of 1 to 5 might be used where a rating of "5" indicates the preservation action has a large impact on the LOS and a "1" rating is given for service levels where the preservation action has very little impact as presented in Table 3. The scoring system should account for customer expectations, regulatory requirements, the agency's strategic mission and objectives, and available resources. This approach was adopted not only for illustrative purposes, but also because it provides a method to rate each preservation action against the agency's LOS goals.

Table 3. Levels of Service Ratings

Levels of Service Ratings						
LOS / Ratings	**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 and/or the traveling public.	impact on the vulnerability to technological or natural hazard.	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	impact the ability to keep the tunnel open and operational.	impact safety of workers and/or the traveling public.	impact the vulnerability to technological or natural hazard.	increase the remaining life of the asset.	improve the experience for the driving public.	impact the potential for environmental impacts
	The improvement will moderately:					
3	improve the ability to keep the tunnel open and operational.	improve safety of workers and/or the traveling public.	reduce the vulnerability to technological or natural hazard.	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 and/or the traveling public.	reduce the vulnerability to technological or natural hazard.	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 and/or the traveling public.	reduce the vulnerability to technological or natural hazard.	increase the remaining life of the asset.	improve the experience for the driving public.	reduce the impacts or potential for environmental impacts.

A rating scale from 1 to 5 is fairly aggregate and provides sufficient resolution for setting LOS scores. The ratings are based on subjective judgment of the tunnel owners' trained inspectors and maintenance personnel. The rating is intended to capture the change in performance of the individual component in terms of how the improvement contributes to the overall performance of the tunnel or the tunnel asset. A higher level of specificity in describing each of the ratings will help make the ratings more user friendly.

To obtain an overall score reflecting the impact of the improvement on the agency LOS standards, the individual ratings can be weighted and combined. The weights applied for each LOS should be established by the tunnel owner specifically for tunnel assets. For this example, the agency emphasizes safety above all else, and therefore, weights this goal more heavily than others. The remaining agency goals were assigned weights to total 100% by the AAMT after ranking agency goals and are shown in Table 4.

Table 4. Levels of Service Weights

LEVELS OF SERVICE WEIGHTS						
Levels of Service	**Reliability**	**Safety**	**Security**	**Preservation**	**Quality of Service**	**Environment**
Weight	20%	40%	5%	18%	15%	2%

Equation 1 - Levels of Service Score

The aggregate score can be calculated as follows:

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

LOS = Agency Level of Service Score
R = Reliability Rating
S_a = Safety Rating
S_e = Security Rating
P = Preservation Rating
Q = Quality of Service Rating
E = Environment Rating
W_R, W_{Sa}, W_{Se}, W_P, W_Q, W_E = Weights for Reliability, Safety, Security, Preservation, Quality of Service, and Environment Scores

Where $(W_R + W_{Sa} + W_{Se} + W_P + W_Q + W_E) = 100$

Assuming the ratings are on a scale of 1 to 5, the LOS Score for the improvement is calculated as a weighted average and on a scale of 0 to 100. As an example, consider six tunnel preservation actions identified by an agency in its six different tunnels. The six actions are explained below and rated in Table 5:

- *Ventilation upgrade to meet NFPA 502* – Upgrading the existing aging ventilation greatly impacts 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 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 impact safety and 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 lights greatly impacts preservation; this LOS is assigned a rating of 5. LED lights are much more

energy efficient than the existing lights, making the score for environment a 5. Although the current system provides the needed lighting levels to operate the tunnel, a failure could require tunnel closure. Because of this, 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 impacts safety, and therefore receives the highest possible rating for that LOS. 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 structural deterioration 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 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 impact the quality of service for motorists by improving the sense of openness and improved 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. Though 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 impacts the overall preservation of the tunnel by eliminating any future tunnel issues related to the existing deteriorated ceiling. The security and environment LOS are not affected by this improvement.
- *Install flood gates* – Installing flood gates has the potential to greatly impact 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 potential 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.

Table 5. Preservation Action Ratings and LOS Score

PRESERVATION ACTION RATINGS AND LOS Score								
Levels of Service		**Reliability**	**Safety**	**Security**	**Preservation**	**Quality of Service**	**Environment**	**LOS Score (Eq. 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**

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

Based on the LOS and their associated weights listed above, the highest scoring improvement in the list above is repairing the active leak in Tunnel 4. This is due to the high score given to the Safety (40%), Preservation (18%), and Quality of Service (15%) goals. The second highest scoring improvement was for removing the existing concrete tunnel ceiling in Tunnel #6, resulting from the high ratings applied to the heaviest weighted LOS.

3.6.1.1 LOS Score Sensitivity

A considerable amount of variability is permitted in the LOS Score. The agency has the ability to select the applicable LOS standards, establish weights to emphasize relative importance, and to rate the preservation action in terms of its impact on the selected LOS. Given these multiple factors, it is likely that different personnel calculating the LOS Score will obtain differing results. For this reason, the sensitivity of the resulting scores is important to understand.

To test the sensitivity, we reconsidered the ratings as they might have been interpreted by another person and recalculated the scores. The results were very similar. Repairing the active leak in the tunnel remained the top scoring action with the other two actions scoring similarly to the first user's ratings, presented in Table 5. Several iterations of different LOS ratings to mimic different users on the complete set of preservation actions (Appendix D of the Guide) was conducted with similar results. This indicates that the LOS Score is not highly sensitive to varying inputs for a given set of LOS with the same weight distributions.

If the LOS distributions were changed, e.g., to highly emphasize safety (65%), reliability (20%), and preservation (15%), and to eliminate the other LOS, the scores would vary considerably. This is to be expected, though, since the improvements that impact the LOS with greatest weights would receive higher scores. In this case, the preventive actions with a high impact on safety increased greatly in score. LOS scoring and prioritization are heavily dependent on the weights applied to the levels of service goals. The same levels of service and weights must be applied to all preservation actions to be compared.

3.6.2 Cost Effectiveness

Cost plays an important role in the prioritization of tunnel improvements. Actions with low initial costs are often selected before higher cost improvements, either due to funding limitations or to address the "low hanging fruit" and maximize the number of preservation actions that can be accomplished. Cost considerations need to include the life-cycle costs, which reflect additional costs or cost savings (such as possible reductions in energy or additional maintenance[22]) over the life of the asset. To allow for an evaluation of improvements for assets with varying lifespans (years), the life-cycle cost can be represented as annualized equivalent cost. This allows a light fixture replacement project to be compared with the replacement of a fan motor.

The other factor that needs to be considered is the number of users affected by the preservation action. The greater the traffic volume in the tunnel, the higher the risk of accidents or incidents if there is a failure of a tunnel system, and the greater the impacts on the traveling public (in terms of users' loss of time, etc.). Therefore, an improvement for an urban tunnel with high ADT might receive higher priority when compared to a similar cost improvement in a rural tunnel that experiences less traffic. The CE Score uses both life-cycle cost and the number of users. It is based on the cost per user, using the annual equivalent life-cycle cost, calculated using the annualized initial cost minus the benefits derived from the annual savings in energy and maintenance costs over the life of the improvement, and ADT for the number of users.

To calculate the CE, for each preservation action, provide the following items, as applicable, to that action:

- 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) – this is used to add agency costs into overall project cost
- Change in annual costs considering energy, maintenance, closures, reduction in accidents, reduction in staff, etc.
- ADT
- Service life after improvement (the number of years to which the annualized cost applies)

Equation 2 - Annual Life-Cycle Cost

The annual life-cycle cost is computed as follows:

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

ALCC = Annual Life-Cycle Cost, \$ per year
C = Capital Cost + Agency Oversight Cost, \$
i = Discount Rate, %

n = Change in Remaining Life Resulting from Improvement, years
A = Annual change in costs (costs associated with energy, maintenance, closures, reduction in accidents, reduction of staff, etc.), $. (Negative if savings)

The discount rate used when calculating the annual life-cycle cost is a simplification allowing for the incorporation of the time value of money into the CE Score. A discount rate, or opportunity cost, is generally determined based on the real rate of return, inflation, and risk premium. Risk premium pertains to the possibility that the projected cash flows will be less than estimated. For the purpose of this metric, risk premium can be assumed as 0 since all compared actions are within the same agency and state; therefore their risk is all comparable. Historically, the real rate of return has been assumed as 3%. Inflation also is generally assumed to be 3% for similar calculations. Since changes in maintenance and energy costs are entered into the worksheet in real terms (without inflation considered), the discount rate should match the real rate of return. Accordingly, a discount rate equal to 3% has been used in the following example and is recommended unless alternative data is available.

The CE Score, which is intended to reward improvements with lower costs per user, is a score based on the inverse of the ratio of the cost per user, such that high costs per user return lower CE Scores. CE is calculated as follows:

Equation 3 - Cost Effectiveness

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, varies (Section 3.6.2.1)

Table 6. Cost Effectiveness Score

COST EFFECTIVENESS SCORE										
Preservation Action (PA)	**Tunnel #**	**Capital Cost ($)**	**Agency Oversight Cost ($)**	**Annual Change in Costs ($)**	**PV of LCC ($)**	**Remaining Life due to PA**	**ADT (x 1000)**	**Annualized Life - Cycle Cost ($) (Eq. 2)**	**Annual Cost per Daily Vehicle ($)**	**CE Score (Eq. 3)**
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**

Discount Rate = 3%

Cost Factor, F = 10

As shown in Table 6, the low cost of the repair for the CO sysem 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 this improvement. The high costs of the ventilation upgrade, new LED lights, removing the tunnel ceiling, and installing flood gates contribute to their low CE scores.

3.6.2.1 Calibrating the CE Score

Once all the required data has been entered into the CE Score table, it is necessary to calibrate the final score to ensure practical scores are distributed over a distinguishable range and to offer an accurate and fair assessment of cost effectiveness.

A value of 10 was assigned as a multiplier of the annual cost per daily vehicle, the Cost Factor, F. This number was selected based on the sample data in the spreadsheet 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, this value is adjusted to provide meaningful scores that:

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

The user can adjust the multiplier until the scores fit the desired outcomes. Once the value has been selected by the user, the CE Score section of the model is complete.

3.6.2.2 Sensitivity of Cost Effectiveness Score

The CE Score will vary depending on the inputs for Capital Cost, Annual Change in Costs, Remaining Life, and ADT. Tests were performed where the values for these parameters varied by up to 25%. Changes in capital and annual energy and maintenance costs of up to 25% had little effect on the final CE Scores. The largest effect was where the initial capital cost is high, and a 25% increase is substantial. In these cases, the final CE Score increased appreciably, (e.g., under 10 to under 20) but the ultimate range of scores did not change considerably, and the ordering of the improvements in terms of scores was not affected.

When Remaining Life estimates were increased by 25%, the resulting CE Score changed most significantly for the high cost improvements, where the additional years allowed costs to spread out over longer periods. In these cases, the CE scores increased. However, the overall ordering of the preservation actions did not change appreciably.

For ADT, an increase reduced the ALCC per user, which resulted in a higher CE Score. This would be expected. High cost improvements benefited the most, increasing in value substantially; however, the overall range of scoring for the overall group did not change significantly due to the normalization process.

3.6.3 Implementing the Most Urgent Improvements

When evaluating tunnel preservation priorities, the most urgent improvements should receive high 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. Upgrading to meet a new code requirement or design standard may also be a priority for the agency. The RBU Score, the third component contributing to the overall MOE, is determined by considering the following factors:

RBU:

- How much of its service life has the asset expended?
- What is the asset’s current condition?
- Is the preservation action required to comply with a regulatory requirement or is a design standard for new tunnels an agency goal to be implemented in existing tunnels?
- What is the associated risk of an unplanned event occurring if action is not implemented?

3.6.3.1 Remaining Life vs. Service Life

To evaluate the asset’s age and 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.

The age data used for each improvement should be based on expert input and past experience. While original service life information for some elements, such as tunnel structure, need to be estimated by an experienced engineer, the service life information for other system elements, such as tunnel lighting, can be obtained through the manufacturers. Using the element's date of installation, the remaining life can be evaluated. To develop consistent and replicable ratings, the remaining life and original service life must be carefully defined and operations personnel must be trained in their use.

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. For example, the average expected service life for most major electrical equipment is assumed to be approximately 40 years. Appropriate adjustments can then be made to account for performed maintenance and operating conditions. Chapter 37 of the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) 2011 handbook, *Heating, Ventilation, and Air-Conditioning Applications,* details service life estimates and provides some assistance estimating service life for other tunnel assets. These values may also be assessed based on previous experience, historical data, or manufacturer's recommendations.

Percent of life expended is calculated as the ratio of asset age to its original service life, or the original service life minus the remaining life, divided by the original service life. For example, if fan drives have an original service life of 50 years and a remaining service life of 15 years, the percent of life expended is 70%.

The percent of life expended alone does not define the urgency of the improvement. The condition of the asset must be considered.

3.6.3.2 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 using any of these sources or a combination of them to provide an assessment of the existing tunnel asset prior to developing the list of needed improvements. Such conditions can be established by following the guidelines of the 2015 Specifications for the National Tunnel Inventory.

Conditions of the existing asset or tunnel system should be categorized as good (CS1), fair (CS2), poor (CS3) or severe (CS4) for simplicity in determining the RBU Score. These conditions are input as 1 through 4.

3.6.3.3 Codes and Standards 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 code 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 7.

3.6.3.4 Risk of Unplanned Events

For each preservation action, the risk of an associated unplanned event should be assessed. Extreme weather, flooding, fires, and seismic events are among the many unplanned events that might occur. Tunnel owners should consider the risk of these events and their possible impacts and proactively 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.

Table 7 displays the information used to develop the RBU Score.

Table 7. Risk-Based Urgency Score Considerations

RISK-BASED URGENCY SCORE CONSIDERATIONS							
Preservation Action	Tunnel #	Remaining Life	Theoretical Service Life	% Life Expended	Condition (1 to 4)	Regulatory Compliance Issue?	Risk of Unplanned Event (1 to 3)
Ventilation upgrade to meet 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 tunnel	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 not applicable (N/A) whenever the proposed preservation action is installing a component that is new to the tunnel system.

3.6.3.5 Risk-Based Urgency Score

The RBU, on a scale of 0 to 100, is calculated based on a user-input rating of 0 to 10 for urgency, where 10 indicates an action that is very urgently required and 0 indicates an action that would be beneficial, but is not necessarily urgent at the time of the analysis. Urgency ratings are subjective, considering the percent of life expended, the current condition of the asset, the risk of an unplanned event, and upgrading assets for regulatory compliance when this is an agency priority. The assessment should be performed by the AAMT, with the specific knowledge and understanding of the various systems and the risks associated with the tunnels.

A rating of 0 to 10 was chosen to provide a range in the ratings, with the intent of multiplying the ratings by 10 to arrive at the final RBU. There was some consideration of changing this range to 0 to 5 or even potentially fewer options, but an alternative scoring can be incorporated based on agency experience. With the 0 to 10 scale, it is recommended that the AAMT consider 0 to 10 as five main categories, as shown in Table 8. Once the Urgency Category is reduced to Extreme, High, Medium, Low, or Non-Existent, the ratings can be more readily assessed within the category as the bottom, middle, or top of the set range.

Table 8. Assigning RBU Ratings

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.	Non-Existent	0

Once the rating of 0 to 10 is assigned, the RBU is calculated by multiplying this value by 10 to attain a 0 to 100 score. The worksheet provided in Table 9 shows the example RBU Score calculation for the same six preservation actions analyzed in the previous sections.

Table 9. RBU Score

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 (1 to 3)**	**Urgency (1 to 10)**	**RBU Score**
Ventilation upgrade to meet 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 tunnel	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**

*The condition is rated as not applicable (N/A) whenever the proposed preservation action is installing a component that is new to the tunnel system.

3.6.3.6 Calibrating the Risk-Based Urgency Score

The RBU Score is determined subjectively. The scores are further aggregated by multiplying a factor of 10. The AAMT's determination of the urgency appears to have a significant impact on the final prioritization. While the RBU Score is determined subjectively, it must be arrived at by logically looking through the RBU considerations. Once these considerations are identified, each preservation action's associated urgency can sensibly be determined 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), and extreme (RBU rating of 10). The rating can then 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. Although a variance of two points results in a 20-point RBU Score variation, the RBU Score is only one of three scores used to determine the overall MOE Score. This potential variance, however, further emphasizes the need to have a group such as the AAMT consistently perform the RBU assessment.

3.7 Calculation of Aggregate Measure of Effectiveness (MOE)

The LOS Score, the CE Score, and the RBU Score are each on a scale of 0 to 100 and can be combined as an aggregate score to measure the effectiveness of the proposed improvement or maintenance. The aggregate MOE is then used to prioritize preservation activities. The combination of the three scores allows weighting each score to reflect the agency's overall goals. Weighting can be obtained by expert judgment or using techniques such as the Analytical Hierarchy Process (AHP). AHP uses a pairwise comparison of the relative importance of each measure to consistently evaluate each of the measures and then computes the weights[(23)]. Other methods for developing weights include Multi-Attribute Utility Theory (for example see Zietsman et al, 2006[(24)]) and Delphi methods.

Once the weights are established for the agency, an overall score, or MOE, of the improvement is computed as a weighted average.

Equation 4 - Measure of Effectiveness

MOE Score = W_{LOS} * LOS + W_{CE} * CE + W_{RBU} * RBU, where

LOS = Level of Service Score
CE = Cost Effectiveness Score
RBU = Risk-Based Urgency Score
W_{LOS}, W_{CE}, W_{RBU} = Weights for the LOS, CE and RBU
Where (W_{LOS} + W_{CE} + W_{RBU}) = 100

Utilizing weights for LOS, CE, and RBU of 35%, 20%, and 45%, respectively, the MOE Scores for the example six preservation actions would be as follows in Table 10:

Table 10. MOE Score

MEASURE OF EFFECTIVENESS SCORE					
Levels of Service		**Levels of Service Score**	**Cost Effectiveness Score**	**Risk-Based Urgency Score**	**MOE Score (Eq. 4)**
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 tunnel	4	89.0	100.0	70.0	**82.7**

MEASURE OF EFFECTIVENESS SCORE					
Levels of Service		**Levels of Service Score**	**Cost Effectiveness Score**	**Risk-Based Urgency Score**	**MOE Score (Eq. 4)**
Weights		35%	20%	45%	
Preservation Action	**Tunnel #**				
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**

The resulting MOE Scores are used to develop the agency's prioritization plan.

3.8 Method to Prioritize Preservation Actions

Because the calculated scoring described above normalizes all improvements on a consistent scale, it facilitates the comparison of the MOE Scores to prioritize actions. By including ADT in the calculation for the CE Score, improvements in urban areas where traffic is greatest receives higher priority. By annualizing the costs, improvements that have a short service life can be compared with those that have extended service lives. The LOS Score reflects how well the preservation action addresses the agency's overall goals and objectives. The combination of the three scores into one MOE allows each alternative activity to be weighed against the others and prioritized.

The example in Table 10 results in the following prioritization:

1. Repair active leak in tunnel (Tunnel 4) – Repairing the active leak has a very high impact on the agency's LOS while having a low annual cost per daily vehicle, even though Tunnel 4 has the lowest ADT of the agency's six tunnels. The urgency is rated as moderately high as well; therefore, this preservation is calculated as the top priority.
2. Remove existing concrete tunnel ceiling (Tunnel 6) – While an expensive action, removing the existing concrete tunnel ceiling receives the maximum RBU Score due to being in poor condition and at the end of its service life. This improvement also helps the agency achieve its goals and objectives, therefore it is prioritized second.
3. CO System – repair to operating condition (Tunnel 2) – Repairing the CO system is inexpensive and moderately affects agency goals and objects and is moderately high with regard to risk-based urgency. Even though the ventilation upgrade has higher LOS and RBU scores, its higher cost ranks it lower than the CO system repair.
4. Ventilation upgrade to meet NFPA 502 (Tunnel 1) – While the ventilation upgrade receives the lowest CE Score, due to its high cost, its moderate LOS Score, and high RBU Score prioritize it fourth. While the current system is in good condition, it has expended much of its service life and the owner wishes to upgrade to meet NFPA 502 requirements.
5. Install flood gates (Tunnel 6) – Installing the flood gates is expensive and receives one of the lower LOS scores. However, the RBU Score for the flood gates is higher than installing new LED light due to the high probability of an unplanned event occurring.

6. Install new LED lights (Tunnel 1) – Replacing lights with new LED lighting is not considered an urgent improvement, and given that RBU is weighted highest of the three scores, this results in the lowest score for the LED lighting improvement. The new lighting does address the agency LOS well, but LOS only contributes to 35% of the overall score. Therefore, the LED lighting improvement ranks sixth of the six preservation actions.

This methodology provides guidance to a tunnel owner for setting priorities. However, prioritization and programming for the next five 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 after several high cost improvements are programmed. Essentially, the projects that represent “low hanging fruit” that can be accomplished easily might receive 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 of time will likely be grouped with other activities within the same tunnel that can be accomplished during the same service outage. There are many factors that go into an owner’s ultimate decision on priorities, but the MOE methodology presented above provides a first pass that can assist an owner in making decisions.

3.9 Use of Metric for Evaluation of Alternatives

Inherent in the metric is the ability to evaluate various alternatives for one tunnel preservation option. Similar to the process of prioritizing multiple preservation actions, the MOE Score can be utilized when evaluating these alternatives. This type of analysis considers alternatives used to select a single preservation action. Examples of this include lighting replacement (LED vs. high-pressure sodium or other systems), fire alarm upgrade, SCADA systems, and different methods of waterproofing. Typically, life-cycle cost analysis is used to evaluate alternative improvements. The use of the metric to calculate a MOE Score allows an agency to consider its goals and objectives (LOS Score), annual cost per user (CE Score), and urgency (RBU Score) when comparing alternatives, which may be beneficial instead of only considering life-cycle or capital costs.

3.10 Use of the Metric to Determine Appropriate Funding and Staffing Levels

Although most highway tunnel owners are faced with limited and generally decreased funding, maintenance must continue to keep their tunnels open and safe for the traveling public. Some tunnel owners have had to decrease their staffs to meet annual budget limits; these are sometimes part of an overall staff reduction within the agency. The MOE calculation outlined above provides the opportunity to proactively forecast funding and staffing needs for tunnels. By utilizing the prioritization resulting from the metric, these levels can easily be calculated for tunnels. The following sections show how funding and staffing levels can be developed for the needed preservation actions.

3.10.1 Funding Levels

Most highway tunnel owners are DOTs or Authorities who also own considerably more assets than just tunnels. Most own bridges, roadways, facilities, and rolling stock for which funding must also be provided. Only one of the agencies interviewed has a funding stream dedicated solely for the operation and maintenance of the tunnels, but that is uncommon. Tunnels typically compete with the agency’s other assets for funding. Therefore, a means of determining tunnel funding needs and communicating those needs within the agency, based on a data-driven approach, is essential.

The methodology for prioritization of preservation actions through an asset management approach presented in the Guide is an appropriate method for assisting highway tunnel owners with developing capital plans that meet the objective to keep their tunnels in good operating condition. This prioritization takes into account all deficiencies identified from regular inspections and the resulting recommendations for repair, whether they be critical, priority, or routine repairs. By using the methodology developed herein, tunnel owners can prioritize all of their tunnels' deficiencies in order of importance. From this ranked order, and based on a general knowledge of funding levels set aside on an annual basis for tunnels, the owner can forecast which repairs are to be included in the forthcoming capital plans and insert these costs, along with planned preventive and periodic maintenance costs. Table 11 presents a selection of the agecy's prioritized list of preservation actions and associated labor costs for funding levels discussion. A complete listing of the agency's preservation actions is provided in Appendix D of the Guide.

Table 11. Funding Evaluation with Labor Costs

FUNDING EVALUATION WITH LABOR COSTS															
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 Tunnel	4	10,000	50	5,000	0	-	1,000	1,000	6,000	5,000	11,000	1	-	11,000
2	CO System – Repair to Operating Condition	2	32,000	80	25,600	0	-	3,200	3,200	28,800	6,400	35,200	1	-	35,200
3	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	1	-	6,270,000
4	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	2	264,000	9,064,000
5	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	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

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

Final preservation implementation priority is determined by the agency and ultimately based on available funding. Two approaches to tunnel preservation funding are considered, top-down and bottom-up. Top-down funding is allocated by upper management based on a formula percentage of the overall transportation funding. In a bottom-up funding scenario, after the analyses of the identified tunnel preservation actions, the improvements can be prioritized and implemented into the agency's capital plans. The costs can assist the agency with projecting capital expenditures for tunnel preservation for several years. Looking at the preservation actions presented in Table 11, top-down and bottom-up funding can be discussed further:

- Top-down funding – The agency has set the budgets for the next 3 years for tunnel improvements to be $7 Million for Year 1, $10 Million for Year 2, and $13 Million for Year 3. With the available budget, the preservation actions for years 1 through 3 presented in Table 11 can be performed with significant available budget remaining for other smaller scale repairs during years 1 and 2. The new LED lights and flood gates planned for year 3 are more expensive and leave approximately $200,000 available for small-scale improvements as well.
- Bottom-up funding – Based on the preservation actions shown in Table 11, the required budget for tunnel improvements for Year 1 is $6,316,200; the budget required for Year 2 is $9,064,000; and the budget required for Year 3 is $12,794,454.

Ultimately, it is important that top-down and bottom-up funding considerations come together for an effective funding process. In an ideal situation, there would be adequate funding to implement all of the needed preservation actions, but this is rarely the case.

3.10.2 Staffing Levels

Interviews with six large tunnel owners and knowledge of other owners' operations indicate that current staffing levels are based on overall agency needs, and not just tunnel needs. Many tunnel owners categorize tunnels as a subset of bridges and use the same personnel to respond to needs for both. Other tunnel owners have dedicated tunnel staffs, whether on a statewide, regional, or tunnel-specific basis. Staffing levels usually remain fairly constant from year to year, but may be adjusted from time to time due to the agency's overall commitment to reduce staff by a certain percentage.

Two of the agencies interviewed are currently assessing the efficiency of tunnel support personnel using maintenance tasks typically accomplished on a daily basis. This will provide valuable information for these agencies to determine the amount of staff generally needed to meet the demands of tunnel maintenance. Other agencies have been operating their tunnels with a fairly consistent number of staff members throughout the years. At least one tunnel owner interviewed suggested that fewer staff is needed than in the past, as some functions have become automated instead of manual. But all owners interviewed clearly stated that when personnel are not available for maintenance and preservation tasks, the owner uses external consultants or specialty contractors to complement agency staff.

Many tunnel owners are using or considering using computerized maintenance management systems (CMMS) to schedule and track both preventive and periodic maintenance activities. These CMMS also are often capable of tracking staff time to complete assigned tasks. By using this type of technology, the agency can determine the effectiveness of their personnel in completing the required task in an allotted time. Using similar means will provide historical records to document efficiency of agency personnel. Such procedures would also validate the number of personnel needed to carry out functions on a periodic basis, and would provide supporting data for engaging outside consultants or specialty contractors. CMMS also can provide data to support asset management functions.

The prioritized list of tunnel improvements can be utilized to evaluate staffing needs. In evaluating the cost effectiveness of the improvement, both initial costs and changes in annual energy and maintenance costs are calculated. During this cost estimation process, the man-hours needed for the improvements can also be determined. It is necessary to identify which tasks would be completed by agency personnel and which would be contracted out for others to complete. Even tasks that are contracted out will require some support by in-house personnel, typically in managing and overseeing the work. These staff hours need to be identified and quantified to determine the contribution to overall tunnel staffing needs. Table 11 above shows the estimation of agency costs. From the labor costs indicated for each improvement, an estimate of agency man-hours could be developed, which could be expanded to determine specific staffing needs.

The example in Table 11 can be used to show the determination of staffing needs. First, the type of agency personnel should be identified (management, maintenance, etc.) and classifications established for each. For each improvement listed, beginning with the highest priority, the number of staff hours needed for each classification should be estimated. In this manner, it would be readily apparent how many staff members would be needed to accomplish the improvements in Year 1, Year 2, etc. However, routine and preventive maintenance requirements must also be included in the estimated staff-hour calculation. The staffing calculation may actually limit the improvements to be included in the Capital Plan. In the case where the funding might be available but there is not adequate staff to accomplish the work, the agency would need to decide if additional staff should be brought on, if a larger portion of the work should be contracted out, or if some improvements might need to wait until the next year.

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 11 shows how the agency labor costs can be determined. Initially, the cost of project labor versus project materials is estimated. Labor can be approximated as a percent of the overall Capital Cost in the absence of more detailed cost backup. 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, in the absence of a more detailed calculation, the AAMT should estimate what percentage of the total labor cost will be agency labor versus labor of contracted personnel. In the examples in Table 11, most of the work requires specialized contractors so the agency will contract out for each of the tasks. The estimated percent is then multiplied by the project labor cost to obtain an estimation of agency labor. The number of staff needed to complete the preservation action can be computed by dividing the agency labor by an average hourly rate considering the staff that would be associated with that work. Agency staffing is provided in Table 12.

Table 12. Agency Staffing

AGENCY STAFFING									
User Defined Priority	Preservation Action	Tunnel #	Total Agency Labor Cost ($)	Agency Average Rate ($/hr)	Agency Man-hours	Cumulative Annual Agency Man-hours	# Full Time Staff Required	Cumulative Annual # Full Time Staff Required	Year Implemented
1	Repair Active Leak in Tunnel	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

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 12 assumes a one-year duration for each of the preservation actions.

CHAPTER 4

Conclusions and Suggested Research

The methodology presented in this research provides a rational approach to tunnel asset management. It sets the overall framework for asset management by establishing agency goals and objectives as well as focusing planned preservation and improvements on these goals. The use of established performance measures applicable to tunnels and their specific systems focuses on areas that will positively impact the agency goals and allows the performance of the overall approach to be monitored and adjusted when needed. Preservation actions are planned and programmed, based on actual inspection findings and tunnel system evaluations, as opposed to being reactive responses to issues as they arise.

Prioritizing preservation actions for tunnels is difficult due to their complexity. In addition to the structural and roadway elements, there are mechanical and electrical systems that rely on a variety of equipment. The metric outlined in the research provides a means of prioritizing preservation actions that apply to different tunnel systems. The metric was developed and evaluated using a variety of sample preservation actions and provides reasonable results. It may, however, be necessary for an agency to calibrate the model using their specific systems and preservation improvements, as discussed in the previous chapter.

Planning for preservation needs involves a number of factors. What goals does the agency have that can be addressed within the tunnels? Improving safety? Improving reliability by minimizing closures of the tunnels? Cost is a major consideration that may come into play when prioritizing improvements, but there is risk in not performing a high-cost action, especially if traffic volumes are extremely high. Factors that must be considered when evaluating alternatives and prioritizing planned improvements are inherent in the metric in the three scores: LOS, CE and RBU. These factors include:

- Agency goals and objectives (LOS) – the actions that positively impact the LOS the most receive highest priority
- Life-cycle cost – lower life-cycle cost improvements receive higher priority
- Traffic – tunnels with more traffic (considered users) receive higher priority
- Risk of unplanned events – the AAMT assesses the risk of floods, earthquakes, fires, and other unplanned incidents
- Remaining life – assets close to the end of their remaining life are assessed in terms of the urgency of the repair or replacement
- Condition – as with remaining life, assets in severe or poor condition receive priority
- Regulatory considerations – improvements that are necessitated due to a regulatory requirement, or that the agency desires to implement in order to address new design standards, can be considered and given high priority if desired

The three scores that result from consideration of these factors allow the AAMT to calibrate the process, by reviewing the ranking of each preservation action for that score and deciding if the ranking is reasonable. The combination of the three scores into one MOE, as outlined in the Guide and in the

Chapter 3 of this report, facilitates the comparison of very different kinds of preservation actions and ultimately leads to the prioritization and the evaluation of funding and staffing.

There are multiple benefits of the methodology derived from this research and of the development of the Guide:

1. Data driven: The approach is based on the findings from inspections and evaluations of the tunnels. It assesses the improvements needed and provides cost and traffic data to include in the evaluation. It relies on inputs from the AAMT and from the actual inspectors evaluating the tunnel systems to provide ratings when employing the metric.
2. Documented approach: The methodology presented herein is documented in *A Guide for the Preservation of Highway Tunnel Systems*, which is complete with multiple examples for use of the metric in prioritizing preservation actions and evaluating funding and staffing scenarios. As such, it provides a process which can be repeated annually, regardless of personnel changes that may occur within an agency.
3. Training tool: As tunnel personnel approach retirement and less experienced staff enter transportation agencies, the Guide provides an easy to understand training tool on the process and steps that comprise tunnel asset management.
4. Flexible approach: The metric addresses potential differences in agency organization and procedures by building in flexibility at multiple stages. For example, the agency assigns its own weights for each LOS and in the ultimate combination of three scores to obtain the MOE. The rating process also employs subjectivity versus a programmed result. The metric’s inherent flexibility is very important since agencies’ existing methods for managing their tunnels vary considerably and there is no one-size-fits-all approach.

This research accomplished the goals to develop a guidance document that: outlines how to develop a comprehensive list of preservation actions, quantifies the benefits of tunnel preservation actions, provides decision-making tools to optimize tunnel preservation actions, and develops a method to determine appropriate levels of funding and staffing to achieve agency selected goals. It is applicable to the preservation of existing tunnels and for preservation planning during the design of new tunnels in both urban and rural areas. Further research opportunities exist to implement and expand on this work, as described below.

4.1 Implementation Plan

For the proposed guidelines to be employed by tunnel owners, it must first be accepted and promoted by AASHTO and FHWA and introduced through various presentations and training workshops to tunnel owners and operators. This implementation plan proposes activities to be performed by the Research Team to introduce the Guide, provide training, and ultimately implement it via a pilot project for a transportation agency with multiple tunnels.

The Research Team has presented the metric and examples of its use during its development to the AASHTO T-20 Subcommittee on Bridges and Structures (SCOBS), at the SCOBS Conference in June of 2014 and again at TRB in January 2015. Upon completion of the Guide, the research should be reviewed, adopted by AASHTO, and should be published by AASHTO as *A Guide for the Preservation of Highway Tunnel Systems*. Publication through AASHTO will promote acceptance and use of the Guide by transportation agencies across the country.

To introduce the Guide to highway tunnel owners and operators, it is suggested that the Research Team introduce the final Guide at a special session of the annual TRB meeting and at AASHTO’s T-20 SCOBS in January 2016. The sessions would acquaint tunnel owners with the Guide and its benefits. The rollout of the Guide will be timely since the TOMIE and Specificaitons for National Tunnel Inventory (SNTI) will be distributed in 2015, and requirements for the NTIS will also be available. A brief PowerPoint presentation providing an overview of the research, including the use of the metric with specific examples, would include the process from the development of preservation actions to prioritization and funding and staffing evaluations.

Additional workshops to provide specific training would be advantageous. These workshops would ideally be in person where the groups could work as teams through the entire process. Using a set of mock preservation actions, the teams would implement the ratings and determine the LOS Score, CE Score, and RBU Score before determining the MOE. Each group would then prioritize their preservation actions and prepare a tunnel program for one and five years using the results. Staffing could also be included in the evaluations. It is recommended that two workshops be conducted, one in the east and one in the west.

In lieu of the workshops described above, training webinars could be conducted via the Internet. These webinars would present an overview of the metric and its uses, and would utilize an example to demonstrate the entire process. As with the in-person workshops noted above, sample preservation actions could be used to develop a one- and five-year tunnel program. For the webinar version of the training, interaction will be limited and therefore, the process would be conveyed in a PowerPoint presentation.

If funding could be made available, it would be beneficial to fully implement the research and resulting guidance documentation in a pilot project for an agency with multiple tunnels. Tunnel owners perform regular tunnel inspections, and with the rollout of the NTIS, there will likely be opportunities to implement this research in conjunction with, or immediately following, their tunnel inspections. The pilot project could begin with development of preservation actions to address inspection findings. A template would be beneficial to develop preservation actions based on the findings and recommendations for remediation. Life-cycle costs and ADT data could also be incorporated into the template and captured as the preservation action is developed. Once the actions are established, the metric would be utilized to perform the prioritization. It would be interesting to compare the results using the metric versus results from an agency evaluation performed without knowledge or use of the metric. This could provide good insight into the benefits and limitations of the proposed methodology. Alternatively, if an agency recently prepared their five- or 10-year capital plan for tunnels, the metric could be employed to compare results with the prioritization and programming already completed by the agency. Using the results of the prioritization of their tunnel improvements, funding scenarios and staffing scenarios can be evaluated. The pilot project would help validate that the process is clearly documented, provides reasonable results, and provides adequate flexibility for a tunnel owner to implement regardless of their organization or operational procedures. The results of the pilot project would be documented in a report for submittal to NCHRP and AASHTO, and presented at a future AASHTO T-20 Subcommittee meeting.

Another mechanism to obtain feedback from tunnel owners is via a survey of agencies who will have implemented the metric. This would be a future activity to be completed approximately one year after the training workshops and webinars are completed. Tunnel owners could be surveyed to obtain feedback on the use of the Guide for establishing priorities and assisting in development of their Capital Plan. Survey questions could focus on the following information:

- Was the Guide easy to follow and clearly documented?
- Was the metric sufficiently defined and adequately flexible to meet your needs?
- Were the results of the prioritization reasonable from your perspective?
- Were there other factors not included in the metric that should have been?

- Did the metric address all possible scenarios for comparing preservation actions? Was it easily implemented?
- Do you see the Guide as a benefit in helping you to systematically quantify both priority needs for the tunnel systems as well as funding needs?
- Do you plan to use the Guide for future tunnel preservation planning to meet your overall agency goals?
- Would you recommend that all tunnel owners review the Guide and adopt all or portions of it to help meet their planning and funding needs, regardless of existing asset management programs?

4.2 Additional Research

The metric proposed as part of this research addresses all of the factors that are considered when comparing alternative preservation actions. It provides research and documentation for establishing agency LOS, and sample tunnel performance measures are included in the Guide. It also provides documentation on calculating life-cycle costs. The RBU Score addresses remaining life, condition, risk of unplanned events, and regulatory considerations. Of these, condition states will be well defined with the rollout of the SNTI, covering all of the principle systems associated with tunnels. The risk of unplanned events and regulatory considerations are fairly self-explanatory. The remaining factor, remaining life, could prove difficult for tunnel owners and the asset management team to assess. Because tunnels are very complex, with mechanical and electrical systems, guidance is needed for establishing service lives for the equipment comprising these systems, so that remaining life can be assessed. Bridges and pavements rely on deterioration curves for evaluating remaining life. Tunnels introduce additional complexity due to the various systems they comprise, but deterioration curves are not needed for these assets if the metric and approach proposed in this research is utilized. However, research providing typical service lives for equipment associated with tunnels would be beneficial to tunnel owners. The research could categorize the tunnel into principle systems (structural, civil, mechanical, electrical, etc.) and list service lives for each of the principle elements included in each system. Various types of ventilation fans and lights would need to be included, as would systems such as fire detection and fire protection. Such research would provide tunnel owners with a resource to use when evaluating the remaining life of tunnel assets.

Additional research might integrate performance measures into the metric, such that the programmed preservation actions could identify the anticipated gain in performance if a particular group of preservation actions are implemented. The current metric relates directly to LOS, allowing a correlation between the implementation of the preservation action and a positive effect on a specific LOS. The ability to make this connection is important when it comes to communicating the need for tunnel preservation and for documenting the improvements that result from their implementation.

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APPENDIX A

Literature Review

The 2011 *AASHTO Transportation Asset Management Guide*[8] provided key information within the chapters for assisting agency's in understanding and implementing an asset management program. Key chapter elements include:

- Chapter 1 – An Overview of the Guide: Discusses why transportation asset management, defines goals for the Guide, lists key management steps for implementation, and provides steps to begin.
- Chapter 2 – Setting Direction for Transportation Asset Management (TAM): Defines setting goals and objectives, obtains organization buy-in to TAM, performs a self-assessment and gap analysis, and defines the scope of asset management within the agency.
- Chapter 3 – Align the Organization: Discusses change strategy, integrates TAM into the organizational culture and business processes, establishes asset management roles, and defines performance measure standards.
- Chapter 4 – Transportation Asset Management Plan: Explains benefits of TAM, provides guidance on updating a TAM plan, and links the plan to existing business processes.
- Chapter 5 – Enabling Processes and Tools for Service Planning: Sets creating agency-wide performance measures, links strategic performance measures to levels of service, growth and demand forecasting, and describes risk assessment and management.
- Chapter 6 – Enabling Processes and Tools for Life-Cycle Management and Asset Preservation: Discusses asset inventory, condition assessment, performance measures, life-cycle asset management, forecasting models, and the four types of maintenance processes.
- Chapter 7 – Enabling Processes and Tools for TAM Integration: Describes program planning and delivery, asset value and depreciation, and sustainability.
- Chapter 8 – Information Systems and Data – Explains TAM information systems, TAM system integration, asset management and enterprise resource planning, and data to support TAM.

The framework for asset management was further advanced in NCHRP Project 20-74 *An Asset-Management Framework for the Interstate Highway System* (NCHRP Report 632).[9] The objectives of this research were:

- To provide a method that is holistic, i.e. applicable to existing facilities and those to be developed in the future.
- To provide a basis for making decisions across asset classes in an integrated manner and from a system-wide perspective.
- Be easy to implement, cost effective, and sufficiently beneficial to be attractive for adoption by transportation officials and agencies nationwide.

Report 632 expanded upon the framework from the 2002 *AASHTO Transportation Asset Management Guide* by addressing the following concepts:

- Introduced risk management as part of the decision-making process.
- Suggested owners should report conditions based on the degree assets are functioning as intended, i.e., a maintenance LOS.
- Encouraged a performance-based approach for decision making by establishing performance measures related to preservation, mobility, safety, and environmental considerations.
- Described 13 tools available for asset management, which include AASHTO's AssetManager NT (investment analysis) and AssetManager PT (needs and project evaluation).

- Provided implementation guidance for managing highway investments through policy and strategic focus, program and project prioritization focus, operational management focus, and work category focus.

To establish the framework for asset management, an owner must first define the expectations for Levels of Service (LOS). **NCHRP Project 20-74A *Development of Levels of Service for Interstate Highway System* (NCHRP Report 677)** [(10)] defines LOS as follows:

> *Level of Service: In the context of asset management, this term is synonymous with service level. Although there is the potential of confusion with the identical term used in traffic studies (i.e., traffic LOSs), highway maintenance agencies have been using the term "level of service" for many years to describe the condition of roadway and roadside assets and the quality of maintenance services. Although "level of service" and "service level" can be used interchangeably, "level of service" will be used throughout this report. The term is nearly synonymous with performance measure, but there is a subtle difference in usage. In practice, LOS is used to characterize the performance measure by assignment of a letter grade or score to a specific performance measure or range of measures.*

The report provides examples of LOS standards for varying element or functional condition, indicator (structural adequacy and safety, serviceability, etc.) measure (sufficiency ratings, load ratings, condition assessments), and service thresholds (average NBI ratings) for the asset classes of pavements, structures, drainage systems, roadside, traffic control and management devices (passive), mobility, and safety. The report also states that "tunnels were not included as an asset class for LOS purposes because they are not included in the CoRe elements by AASHTO, and they occur in relatively small numbers on the interstate highway system."

The report concludes with implementation considerations of:

- Pass/fail versus a quantitative approach for LOS analysis. For example, a pass/fail LOS indicator for guiderail could be described as "damaged or missing" or "damaged to the extent that structural integrity is reduced," whereas a quantitative approach for the guiderail could be described as "linear feet of deficiency per shoulder mile" or "percent of guiderails deficient."
- A consideration for data weighting (applicable to tunnels) where a single LOS is desired for a group of assets, such that it may be desirable to assign weights to the average LOS measure for each asset element based on a perceived level of importance of each element. The roll up of this weighting could be used by the owner to prioritize repair actions.

Once LOS are defined by the owner, the next step in the asset management process is to identify performance measures and targets for the various asset classes. Both NCHRP Reports 551 and 706 present research for identifying these performance measures.

NCHRP Project 20-60 *Performance Measures and Targets for Transportation Asset Management* (NCHRP Report 551)[(11)] had the following research objectives:

- To investigate performance measures suitable to asset management
- To develop a framework for establishing performance measures and setting targets for use in asset management.

Performance measurement is a way of monitoring progress toward a result or goal. The Report states "*Performance measures traditionally have been largely technical in nature, capturing an engineering or operational attribute of the transportation system. Today, however, transportation executives and managers must address an increasingly complicated and wide-ranging set of issues regarding the "best" solutions on balance to transportation problems, the cost-effectiveness of proposed projects, and the* *anticipated impacts of these projects. While measures of technical condition and performance are still needed, other types of measures are called for as well. The ways in which performance measures are applied are likewise changing to meet the needs and expectations of stakeholders.”*

Volume I of the research provided performance measures in several categories that delineate the types of measures addressed in the report to facilitate the analysis and discussion of performance measurement in the context of asset management. The categories included:

- Preservation: The condition of transportation systems and actions to keep the system in a state of good repair.
- Accessibility: Ability of people and goods to access the transportation system.
- Mobility: Time and cost to make a trip and the relative ease or difficulty in making the trip.
- Operations and Maintenance: Effectiveness of the transportation system in terms of throughput and travel costs from both a systems perspective and maintenance LOS. Cost efficiency includes measures such as average cost per mile or per vehicle miles traveled.
- Safety: The quality of the transportation service in terms of crashes that are harmful to people and damaging to freight, vehicles, and transportation infrastructure.
- Environmental Impacts: Protection of the environment with performance measures dealing with air quality, groundwater, protected species, noise, and natural vistas.
- Economic Development: Direct and indirect impacts of transportation on the economy.
- Social Impacts: The effects of transportation on neighborhoods adjacent to transportation facilities or on population groups, such as the disadvantaged.
- Security: Protection of travelers, freight, vehicles, and system infrastructure from terrorist actions.
- Delivery: Delivery of transportation projects and services to the customer.

Report 551 also presented guidelines for identifying and using performance measures based upon the asset management principles identified in the 2002 AASHTO Guide. A few of these guidelines that may be of use to tunnel owners include:

Asset Management Principle	Implications for identifying and using performance measures
Policy-driven	Performance measures should be consistent with the criteria used to make resource allocation decisions.
Performance-based	Performance measures used for initial resource allocation and program development should also be used to assist in determining program adjustments.
Analysis of Options and Trade-offs	Performance measures used to guide project selection and resource allocation at the program level should include cost effectiveness and benefit-cost measures, which (where feasible and appropriate) incorporate user costs or benefits.
Decisions Based on Good	Performance measure should describe not only

Information	physical asset condition, but also how assets are serving their intended functions with respect to comfort, convenience, safety, and service.
Monitoring or Provide Clear Accountability and Feedback	Performance measures should be useful for signaling when changes are warranted for strategies and priorities (e.g., in long-range plan updates and in development of capital, maintenance, and operation program budgets). Performance measures should be used to assess quality, schedule, and budget adherence for program delivery.

Volume II of this Report provides a guide for using the performance measure selection and target-setting framework that was developed by presenting several examples.

NCHRP Project 20-57 ***Analytical Tools for Asset Management*** **(NCHRP Report 545)[12]** was undertaken to provide new analytical tools to support asset management. It was developed to assist agencies in making difficult tradeoff decisions for resource allocations while considering asset preservation concerns. The research was conducted in two phases: Phase 1 included a gap analysis with the following objectives:

- To interview staff at 10 state DOTs to obtain a broad perspective on how existing tools are being used and what kind of new tools are needed.
- To review existing analytical tools for asset management and document their capabilities and limitations.
- To assess unmet needs for analytical tools, screening of candidate tool concepts, and selection of two tools for development.

The outcome of this research was the development of AssetManager NT and AssetManager PT. AssetManager NT is a tool to assist transportation agencies in understanding how different patterns of investment in transportation assets will affect performance of the system over the long term. It does not include analytical capabilities typically found in individual asset-specific management systems, such as deterioration modeling, simulation, strategy selection, or optimization.

AssetManager PT is a program-level tool for tradeoff decisions. This tool allows program adjustments to be made in three ways: (1) the user can manually shift projects out of the program or replace them with alternative projects that have been defined; (2) the user can adjust the available budget level for a given program category and have the system automatically shift projects in or out of the program based on the user-specified ranking; or (3) the user can shift funds from one program category to another and have the system eliminate the lowest ranked projects from the category being cut and add the next highest-ranked projects on the list for the program category being increased.

The framework presented in Report 545 illustrates how tunnel asset management data can be used to support tradeoff decisions.

NCHRP Project 08-70 ***Uses of Risk Management and Data Management to Support Target-Setting for Performance-Based Resource Allocation by Transportation Agencies*** **(NCHRP Report 706)[13]** was developed in two parts. Part 1 discussed applications of risk management to support performance-based allocation. As such, it focused on the application of risk management techniques to support funding decisions, such as assisting in prioritizing which projects should be delivered. The report establishes risk tolerances, identifies threats/hazards, assesses impacts or consequences, identifies potential mitigation strategies/countermeasures, prioritizes strategies and develops a mitigation/management plan, and measures/monitors effectiveness of the strategies. Part 2 provides the basis for using information technology tools and data management practices to support data sharing and integration in transportation agencies. Eight DOTs were interviewed and the results were presented as to how they were incorporating information technology into management of their assets.

As systems and infrastructure in a tunnel ages, it is essential that life-cycle costing analysis of systems being considered for repair, rehabilitation, or replacement be included in the evaluation of alternatives for prioritization. A few of the research items present similar methodologies to assist managers in transportation agencies in making informed decisions. **NCHRP Project 08-71 *Estimating Life Expectancies of Highway Assets, Volumes 1 and 2* (NCHRP Report 713)**[14] addresses this concept in detail. Volume 1 establishes how to plan and design for life expectancy models, and how certain states have done this for statewide assets (bridges, pavements, signs, guide rails, etc.). The report also presents several different models, including life-cycle cost models, which could form a basis for life expectancy computations. Volume 2 describes the technical issues and data needs associated with estimating asset life expectancies and the practices used in a number of fields to make such estimates.

The objectives of **NCHRP Project 14-21 *Resource Allocation Logic Framework to Meet Highway Asset Preservation* (NCHRP Report 736)**[15] were to describe in useable terms an analysis framework that Departments of Transportation staff could use to allocate resources across principal categories of highway assets to ensure system preservation, and to demonstrate the framework's application. Applicable conclusions included the following:

- When available funding exceeds preservation needs, optimization is used to distribute allocation for best results.
- When available funding is short of the aggregated preservation needs, the optimization is used to minimize the negative effects of the shortfall on program assets and activities. This usually results in extension of the time required to reach some or all stated performance/condition goals or targets.
- Based on literature review and interviews, each state DOT has unique practices, definitions, account structure, and taxonomies for the allocation of funds to preservation. There is no one-size-fits-all solution.
- Inventory, performance/condition, deterioration, and preservation unit cost data availability for non-bridge and pavement assets is very scarce among DOTs, making it challenging to apply a complete analytical approach for allocating resources, without significant estimating and judgment.
- Agencies track performance metrics and asset inventory in unique ways, so the framework is flexible for a wide range of definitions of both asset-activity groupings and performance standards.
- Good historical expenditure data is needed to estimate unit costs and deterioration rates.
- In a severely constrained situation, optimization is still useful to minimize damage to the net asset condition.
- Deterioration is a very strong driver of preservation need. Where deterioration-based preservation need exceeds funding allocations for any particular asset activity groupings, performance improvement is not possible; rather performance can be expected to regress. In these cases, optimized allocation of available funds would seek to minimize this regression across asset activity groupings.
- The allocation framework does not explicitly incorporate life-cycle cost analysis

- Life-cycle cost analysis is important for determination of preservation strategies, which drives unit costs.

NCHRP Project 12-82 *Developing Reliability-Based Bridge Inspection Practices* (NCHRP Report 782)[16] established goals of developing reliability-based bridge inspection practices for (1) improving the safety and reliability of bridges and (2) optimizing resources for bridge inspection[14]. The reliability-based inspection practices were to provide a new approach to bridge inspections of common design characteristics, and were not intended for unique or unusual bridges such as long-span trusses, cable-stayed or suspension bridges, etc. Specifically, an owner would identify those bridges that are most in need of inspection to ensure bridge safety, and those where inspection needs are less. Then, an interval for inspections could be based on this reliability evaluation instead of a prescribed calendar inspection period.

The reliability-based concept was developed as a three-step process (Figure 2):

- Step 1: What can go wrong, and how likely is it? This step considers design, loading and condition assessments, the likelihood of serious damage occurring into one of four *Occurrence Factors* ranging from remote (very unlikely) with a score of 1 to high (very likely) with a score of 4.
- Step 2: What are the consequences? 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 (i.e. bridge collapse, loss of life) with a score of 4.
- Step 3: Determine the inspection interval and scope. This step prioritizes the inspection needs and assigns an inspection interval for the bridge, based on the results of Steps 1 and 2.

As defined above for LOS, the reliability of having tunnels operational for public use is paramount for an agency's transportation system to function as planned and designed. This same reliability concept proposed for bridge inspection is applicable to inspection of tunnel elements evaluated for risk as indicated in the sample reliability matrix for bridge inspection:

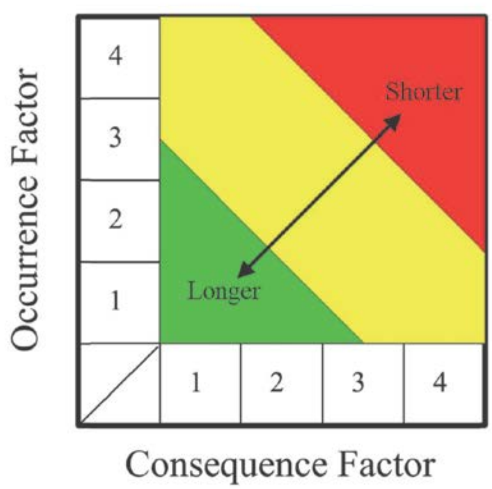

Figure A-1. Reliability Matrix for Determining Maximum Inspection Intervals for Bridges

This conceived approach to bridge inspection provides a methodology to improve safety and reliability of bridges by focusing inspection resources where they are most needed. It also provides for an optimized allocation of resources, as inspection requirements are better matched to inspection needs through a reliability-based assessment.

NCHRP Project 14-24 ***Communicating the Value of Preservation: A Playbook*** **(NCHRP Report 742)[17]** objective was to develop guidance that state DOTs and other transportation agencies could use to formulate and implement strategies for communicating the role and importance of maintenance and asset-preservation in sustaining highway system performance. And, it provides creative ideas for setting up an agency's own preservation campaign.

This 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 Playbook teaches you how to sharpen your communication skills by getting organized around four simple and connected building blocks: (1) audience identification, (2) message design, (3) message delivery, and (4) market research. These are described more fully as follows:

- Audience Identification — Communication is audience-centric, yet many in the transportation arena make the mistake of being so focused on what they want to say or how they want to say it that the most important part is forgotten: what will the message's receiver respond to, remember, and act on? As a DOT, you should start early to identify and segment your audiences so you can find out: what motivates them to action, what words resonate with them, who their trusted sources of information are, and which methods of communication are most effective for reaching them.
- Message Design — Unfortunately, facts and logic alone aren't enough to move key audience segments to action. Your DOT already collects immense amounts of technical data about preservation; you must use this information to create concise and compelling messages that not only deliver compelling facts clearly, but also appeal to the emotions and interests of your most important audience segments and work in multiple delivery channels;
- Message Delivery — More communication mechanisms are available today than ever before. You need to figure out what channels people are using to gather information about transportation. Message delivery should be continuous and will be most effective when you use all three major avenues of delivery including traditional, one-on-one, and new internet media opportunities to effectively communicate messages to your most important audience segments.
- Market Research — In particular, primary research that connects your DOT directly to what stakeholders are thinking, feeling, and saying is the mortar that holds the building blocks of good communication together. A DOT wouldn't use a new maintenance treatment without first testing its performance or subsequently monitoring results; communication is the same.

The ***International Infrastructure Management Manual*** published by the National Asset Management Support Group in New Zealand and Australia, 2011[18], builds upon previous research and actions implemented by numerous transportation agencies and incorporates them into this Manual. It provides numerous examples to aid transportation agencies to utilize asset management for their transportation facilities. It includes five sections, numerous figures, and case studies in the Manual. Sections are provided for:

- Section 1-Introduction to Infrastructure Asset Management: Defines drivers and benefits for asset management, definition of asset management, the asset management process, and how to use the manual.

- Section 2-Understanding and Defining Requirements: Presents the strategic context and the asset management policy, develops and monitors LOS, forecasts future demand, establishes base asset knowledge, assesses asset condition, and identifies critical assets and business risks.
- Section 3-Developing Asset Management Life-cycle Strategies: Presents decision-making strategies, develops operational/maintenance/capital investment strategies and plans, and describes financial and funding strategies.
- Section 4-Asset Management Enablers: Describes the makeup of asset management teams, develops asset management plans, presents information systems and tools, describes service delivery models, defines quality management, and discusses continued improvement.
- Section 5-Country-Specific Issues: Presents the infrastructure overview, regulatory environment, national asset management practices, and transportation initiatives for Australia, Canada, New Zealand, South Africa, United Kingdom, and the US.

Two other references that are pertinent for this project are the tunnel scans that were conducted in Europe in 2005 and the U.S. in 2009. ***Underground Transportation Systems in Europe: Safety, Operations and Emergency Response***[(19)] is the report produced from a scan of European tunnels by 11 personnel from the U.S. who traveled to Denmark, France, Norway, Sweden, and Switzerland in 2005. The objectives of the scan were to learn what is being done internationally for underground transportation systems in the areas of safety, operations, and emergency response. The focus of the scan was on equipment, systems, and procedures incorporated into modern underground and underwater tunnels by leading international engineers and designers. The nine recommendations in the report are centered mostly on design and operational issues related to safety and emergency response, although one recommendation was to use a risk-management approach to tunnel inspection and maintenance of safety-related assets.

NCHRP Project 20-68A (Scan 09-05) ***Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection, and Operations***[(2)] was a scan of U.S. tunnels, and the report offers significant background information that can be used in the tunnel preservation guide that is to be produced as part of this research. This scan included nine members, five of which were from domestic Departments of Transportation, who visited the following tunnel owners as part of the scan: Chesapeake Bay Bridge and Tunnel (CBBT) District, Massachusetts Department of Transportation (MassDOT), the Port Authority of New York and New Jersey (PANYNJ), Virginia DOT (VDOT), California DOT (Caltrans), Colorado DOT (CDOT), Washington State DOT (WSDOT), City of Seattle (DOT and Fire Department) and Seattle Sound Transit System. Calls were also made to the Alaska Department of Transportation and Public Faculties (AKDOT&PF). General topics of interest to the scan team were:

- Current criteria that owners and states use to identify tunnels in their inventory.
- Standards, guidance, and best practices for existing and new roadway tunnels in the US.
- Specialized technologies currently used for existing and new U.S. roadway tunnel design, construction, maintenance, inspection, and operations.

Key observations taken from the scan include:

- Tunnels with functional systems such as ventilation, fire suppression, and electrical and mechanical components are complex structures with more intensive needs for maintenance and operation than traditional transportation facilities.
- A proactive operational financial plan that considers life-cycle costs must be developed to address the need for preventive maintenance, system upgrades/replacements, and operator training and retention.

- Funding for tunnels should not only include buying replacement parts when the tunnel is built, but should also include buying replacement parts that may not be available over time due to obsolescence or other reasons.
- A separate fund should be dedicated to tunnels, and agencies should work with local funding, planning, and maintenance organizations to accomplish the task.

The tunnel owners stated that their regularly encountered maintenance issues attributable to age are defective and obsolete tunnel mechanical and electrical system elements and difficulty in finding replacement parts for the original equipment. Other maintenance issues include:

- Controlling water leaks and other drainage issues
- Electrical system and wiring degradation
- Concrete deterioration and corrosion of embedded reinforcement
- Tile delamination
- Surface obstructions when washing walls
- Difficulty in cleaning light fixtures
- Cumbersome ventilation fan motor drive equipment and plenum dampers
- High maintenance needs for sensors for various monitoring equipment
- Keeping the air ducts free of dust accumulation
- The limited number of cycles that portal doors can withstand

Other issues identified that have a direct bearing on preservation of existing tunnels include:

- Tunnel owners are finding that age-related maintenance needs are increasing regardless of maintenance strategy.
- The owners believe that their current maintenance program is effective, although ensuring adequate maintenance funding is an issue.
- Three tunnel owners (AKDOT&PF, Caltrans, and WSDOT) admitted to deferring maintenance due to budget constraints. Tunnel owners are also taking a number of measures to reduce their tunnel operating costs, including:
    - Moving toward risk-based and condition-based inspections
    - Reducing utility consumption
    - Performing energy audits
    - Aggregating electricity procurement
    - Reducing personnel
    - Moving tunnel operators to a central facility
    - Shifting from unskilled personnel to skilled personnel to handle more work in house
    - Reducing non-critical maintenance activities
    - Reducing labor costs by reducing non-emergency overtime
    - Upgrading mechanical and electrical components during rehabilitation projects
    - Replacing lighting with more energy-efficient sources (i.e. replacing with LED lighting and installing motion sensors to ensure lighting is off when staff are not in the area)
    - Changing fans from chain drive to belt drive
    - Identifying over-height vehicles to avoid tunnel damage
    - Stockpiling parts from obsolete equipment

The Report documented how tunnel owners were using a Tunnel Management System (TMS) to track condition, inspection, repair, and needed funds. The results are as follows:

- The TMS developed for the FHWA/FTA in 2005 is currently being used by five tunnel agencies (DDOT, Oregon DOT, North Texas Tollway Authority, PennDOT, and the Pennsylvania Turnpike Commission) to track tunnel element conditions.
- MassDOT uses a more detailed TMS.
- Three of the owners (AKDOT&PF, CDOT, and WSDOT) use a maintenance management system to track regular tunnel maintenance.
- Caltrans has determined that the relatively small number of tunnels in the state does not warrant the overhead required for an independent TMS.
- VDOT does not currently use a TMS, but is looking into the possibility of obtaining or developing one.

Finally, the Report indicated that the financial management plan for tunnels should not only include initial costs for construction, but also should address future preservation and upgrading needs. The team found that without this dedicated fund, tunnel upgrades do not compete well with system-wide needs, such as traffic signals and pavement preservation.

National Fire Protection Association's **NFPA 502 *Standard for Road Tunnels, Bridges and Other Limited Access Highways* (2008 Edition)**[20] states the following as far as maintaining highway tunnels:

- Section 15.1.1: Fire protection, life safety, emergency ventilation, communication, traffic control, and electrical systems shall be inspected and tested for operational readiness and performance in accordance with the frequency requirements of the applicable NFPA standards or in accordance with 15.1.2.
- Section 15.1.2: Integrated and/or interconnected fire protection, life safety, and emergency systems shall be inspected and tested for operational readiness and performance in accordance with the frequency requirements established by the basis of design or intervals not to exceed five years.

Under Annex A to NFPA 502: The power distribution system should be maintained through an approved annual maintenance program. The electrical distribution maintenance program should be consistent with NFPA 70B Recommended Practice for Electrical Equipment Maintenance, 2010 Edition.

APPENDIX B

DOT Responses to Questionnaire/Interviews

NCHRP 14-27

Guide for Preservation of Highway Tunnels

Responses from Agencies Interviewed

General

1. How do you characterize your tunnels - % in rural and urban locations?

CALTRANS

90% urban and 10% rural

Depends on how you define a tunnel – Headquarters and the Districts may define them differently. Headquarters does NBIS inspections of the tunnel structure and mechanical/electrical equipment for all tunnels in California. California has 12 Districts with the number of tunnels varying from 1 tunnel in a few Districts to 12 tunnels in District 4 (San Francisco Bay Area).

CDOT

95% rural and 5% urban. Colorado DOT has two main tunnels – the Eisenhower and Hanging Lakes; the other tunnels are substantially shorter in nature, are typically not on the interstate system, and do not get the attention as does the two main tunnels. In fact, most funding goes toward the two main tunnels.

MassDOT

100% urban – all in the City of Boston

PANYNJ

100% Urban

The Port Authority has three tunnels in its inventory - the Holland Tunnel, the Lincoln Tunnel and the 41st Street Underpass. The Holland Tunnel was built in 1927 (85 years old) with 2 tubes. The Lincoln Tunnel has three tubes and was built in stages – the first (center) tube was opened to traffic on December 22, 1937 (75 years old), the north tube was opened to traffic on February 1, 1945 (67 years old), and the south tube opened to traffic on May 25, 1957 (55 years old). The 41st Street Underpass was constructed in 1975. All tunnels are within urban locations. The sub-aqueous Holland Tunnel and Lincoln Tunnel link Manhattan to New Jersey (Jersey City and Weehawken, respectively). The 41st Street Tunnel in Manhattan links the Port Authority Bus Terminal to local streets.

VDOT

Total of 9 tunnels as shown below with 14 total tubes. 7 tunnels are urban (78%) and 2 are rural (22%).

- Big Walker Mountain Tunnel
- East River Mountain Tunnel
- Hampton Roads Bridge Tunnel
- Monitor Merrimac Memorial Bridge Tunnel
- Elizabeth River Midtown Tunnel (ERC Maintains – and building one new tube)
- Elizabeth River Downtown Tunnel (ERC Maintains)

- Rosslyn Tunnel
- I-564 Tunnel
- Christiansburg Tunnel

There are 5 additional tunnels that are owned by VDOT, but not under VDOT's maintenance responsibility. These include:

- Chesapeake Bay Bridge Tunnels (2 separate tunnels) – only tolled tunnel
- Airport Road Tunnel, Roanoke
- Colonial Parkway Tunnel, Williamsburg
- Bluff Mountain Tunnel on the Blue Ridge Parkway in Amherst County

WSDOT

43 tunnels that WSDOT is responsible for. 75% urban – 33

25% rural – 10

2. How do you maintain your tunnels- through the use of internal forces or through external contracts?

CALTRANS

We use both internal and external contracts, when required.

CDOT

Internal

MassDOT

Preventive maintenance is a blend of approximately 60% internal and 40% external. Cleaning walls, changing belt fans, changing out pumps, etc. are performed by internal personnel. Correcting leaks with grout injection, replacing lights throughout tunnel, and major outages are performed by external contractors.

PANYNJ

Maintenance activities are performed by a mix of in-house facility and PANY&NJ engineering and facility maintenance staff, call-in contractors, and publicly advertised/bid/awarded contracts. On-call contracts include specialty structural, electrical/mechanical repairs, especially those of an emergency nature.

VDOT

VDOT has just contracted with ERC for a 50+ year long-term operations and maintenance contract to maintain two urban tunnels under the Elizabeth River; VDOT personnel will oversee this contract. VDOT is also in the process of constructing a new tube in the Midtown Tunnel. VDOT has established three different regions for maintenance of their tunnels - eastern region (urban area), western region and northern region – any preventive maintenance work is delegated out to the crews from these regions. All tunnels are within 30 miles from where crews are dispersed. Regular tunnel maintenance is performed by internal forces, but external contracts are used for large or complex maintenance tasks, upgrades, and repairs. For example, internal crews check drainage pumps for operation; but, if they fail, VDOT contracts out to repair.

WSDOT

Mainly internal with regional maintenance forces throughout the 6 regions of WSDOT. For large capital projects, will use external contracts. Majority of tunnels are in the Northwest region. The rest are located throughout the state with some regions only having one tunnel. Tunnels are inspected fully on a 4-year cycle.

3. Are you deferring preventive maintenance or other preservation actions in your tunnels because of funding limitations?

CALTRANS

Inspections for all tunnels are accomplished by Headquarters personnel from Caltrans. Reports with recommendations are generated from these inspections and passed along to the Districts where the tunnels are located. Each District will prioritize preventive maintenance or preservation actions based on the lists of repairs received from Headquarters. If recommendations are primarily routine maintenance, the District will perform these functions with their own internal funding. If the listing of deficiencies is quite large, then the District will provide a request for funding to Headquarters for correcting the deficiencies based upon knowledge of how many dollars may be available that year for repairs. If all repairs will extend beyond one year, then the District will prioritize the repairs over a number of years until all repairs are made. If repairs are needed but go beyond current budgets, the District can request that special funds be used to make the repairs.

CODOT

Yes, predominantly for preservation actions.

MassDOT

Yes and no, not due to funding directly but the ability to hire staff and contract projects. Tunnels generate annual revenues of approximately $300 million, all of which is used for the tunnels. We are under staffed after merger with Massachusetts Turnpike Authority to handle all facilities. There is currently a hiring cap within the organization.

PANYNJ

Yes. The inspection reports identify both priority and routine repairs for both mechanical/electrical equipment and the tunnel structure, where preservation actions can be delayed due to funding. Preventive maintenance delays also encompass roadway repairs.

VDOT

Yes for both issues. A tunnel is a confined space and in order to do any work within the roadway, you have to have a lane closure, which only occurs at certain times of day. We are constrained by both funding and traffic considerations in the urban area, where Average Daily Traffic (ADT) may approach 100,000. Usually, work is not accomplished on weekends, but will be deferred until an appropriate time. More than 70% of preventive maintenance such as checking oil in fans, exercising generators, roadway drainage, cleaning of walls, etc. in the eastern region is performed by internal staff. Preventive maintenance on generators, fire pumps, fire mains, mechanical flow tests, and fire alarm systems are contracted to outside contractors. VDOT initiated an external contract about a year ago to a generator company to perform annual service to their diesel generators.

WSDOT

Yes. There are two tunnels on I-90 at Mt. Baker (one built in 1940). The mechanical/electrical systems get deferred maintenance when upgrades are required. Preventive maintenance is a lower priority when prioritized against other needs. Also funding for maintenance on tunnels was not covered by FHWA in the past.

4. Are you phasing repairs and rehabilitation of your tunnel assets over multiple years due to funding constraints?

CALTRANS

For the tunnel structure, no phasing occurs. Repairs are made as quickly as we can make them. Based on the response for Question 3, there are some delays in phasing many repairs due to monies available.

COLORADO DOT

Yes.

MassDOT

Yes, the capital plan takes that into consideration. The Capital Plan currently includes about $1.0 Billion for repairs over the next five years. Traffic management and timing are key as we must keep the tunnels open for airport access. We will continue to update the Capital Plan yearly.

PANYNJ

Yes – Phasing includes hours of work in the tunnel.

VDOT

Yes, through a 6-year integrated capital plan. Update plan yearly but review it monthly.

WSDOT

Yes. Tunnel maintenance is folded in with asset management for bridge structures. The agency uses a 10-year plan, develops a priority list of repairs to be made, and addresses issues based on need and urgency.

5. Are you experiencing an increase in preventive maintenance costs due to aging of your tunnels and their systems?

CALTRANS

Yes, since many of the older systems are requiring more maintenance to keep the systems operational.

CDOT

Yes.

MassDOT

Not as significant as I expected at this time. The open cut tunnels on I-93 seem to be aging more quickly than the subaqueous tunnels due to higher humidity, which causes increased deterioration, especially in the reinforcement steel.

PANYNJ

Aging infrastructure requires ever-increasing capital investment to maintain

the required service conditions and structural integrity.

a. Investments need to be balanced between active asset replacement and maintaining state-of-good-repair.

b. A constrained maintenance budget and staffing leads to a costly "fix as fail" reactive approach, rather than well-planned asset replacement or comprehensive rehabilitation.

Holland Tunnels – approaching category "b" in emergency mode for mechanical/electrical and life safety equipment. Replacing oil in fans, etc. is critical for fan performance. Housekeeping, gardening, and incidental issues are tending to be put off.

Holland and Lincoln Tunnel Ventilation Buildings are also part of the infrastructure to be maintained as part of the maintenance cost due to regulations for the Authority's recommended code compliance assets, such as backflow preventer valves, sprinklers within the buildings, etc. These buildings are continuing to require maintenance and are continually squeezing other maintenance costs.

Roadway issues within the Lincoln Tunnel and the roadway approach helix also absorb part of the maintenance needed funds. Repaving of the tunnel slabs in the north and south tubes of the tunnel have been performed within the last five years. The center tube roadway slab needs to be repaved in the near future.

The Authority's funds for preventive maintenance or preservation actions are based on the State of Good Repair Index for structures. If an element does not score high, it will get deferred for either maintenance or preservation. If the score indicates more immediate actions or priority repairs are required, this will get the most attention.

VDOT

Yes, through actions required for ventilation and SCADA systems for update. The Department feels they are in a current position to determine what are best actions to perform and update regularly.

WSDOT

Yes. Some of our tunnels have tiles on the walls for enhanced visibility. Although these may be decorative, they do require preventive maintenance to keep them clean. We have experienced increased maintenance on the lighting system. Also, equipment is aging and is wearing out more quickly.

6. Do you anticipate major expenditures on older tunnels in the future where an asset management approach in prioritizing preservation actions might be beneficial to you?

CALTRANS

I think it is intuitive that older structures require more expenditures than newer tunnels. Currently, our Districts take a reactionary approach to fixing when something breaks down. I would like to see a more rigorous systematic preservation approach being used. We do look at the performance of motors and can predict when greater measures may need to be taken. However, this does not mean that the Districts program for this until the motor has failed and is out of service.

CDOT

Yes. We have already experienced some increased expenditures, especially toward tunnel systems. These include lighting, transformers, switchgear in the harsh environment and where equipment is outdated such that no parts are available.

MassDOT

Not at this time. Currently have a Maintenance Management Information System (MMIS) that generates reports each month showing which work orders are open or closed. We average 12,000 preventive maintenance work orders per year, with about 80-90% of these closed per year.

PANYNJ

Yes. Continue preventive maintenance at all times since equipment is well beyond expected life.

VDOT

Studies are being performed currently on many different systems. One of these is for risk assessment in tunnels – what is the cost and effect? Also current studies are assessing the capacities required for the new NFPA Code 502 to see if upgrades are feasible to make.

WSDOT

Yes. With all assets some type of tool for prioritization would be beneficial. This tool would need to be tied to an inspection program because deficiencies are documented from the inspections. Once the rules from FHWA are released, we anticipate a tool would be needed to meet the federal requirements.

7. Do you have a 5-year plan for tunnel preservation actions developed from inspection and prioritization of needs?

CALTRANS

There is not really any plan other than what the Districts program from the recommendations off the inspection reports provided to them. The prioritization is based on risk to the public, risk to the structure, and safety. For example, replacement of lighting to maintain tunnel operations would have the highest priority, because there is an immediate direct risk to the public users. Repairing or replacing fans would have second priority, because the risk is more indirect since there are multiple fans available for contaminate dilution and fire risk is low.

CDOT

Yes. We hire consultants to evaluate the structure, tunnel systems, and estimate remaining life of these systems. Then, this information is used to update the 5-year plan required by the Transportation Commission.

MassDOT

Yes, which is developed from consultant inspections or the MMIS for preventive maintenance. If a preservation action is too costly, it is moved into the Capital Plan.

PANYNJ

The Port Authority has a 10-year capital plan, which is adjusted annually. The Authority forecasts out to 20 years but evaluates needs based on a 10-year plan. The Quality Assurance

Division scans all reports, tracks both immediate/priority repairs if completed, and updates work performed on a quarterly basis.

VDOT

We have a 6- Year Integrated Plan (SYIP). Preservation actions are generated by inspections. Depending upon FHWA's regulations for tunnel inspection, we may have to overhaul our current inspection programs.

WSDOT

Yes, but most of our preservation actions are reactionary to the immediate need. Needs are identified through our inspection program; if needs are categorized as immediate, we address them with our internal staff.

Asset Management Strategy

8. Does your agency have an overall asset management strategy?

CALTRANS

Yes, we do have asset management strategy for tunnels structurally and for routine maintenance for operations. For the structure, it is part of the overall bridge strategy since tunnels are viewed as another bridge project.

CDOT

Yes. We do have levels of service that are primarily established by the Transportation Commission for all state-wide tunnels; these are based on budgets available and are closely tied to average daily traffic (ADT). They also provide advance warning to the Commission for major expenditures needed.

MassDOT

Not to the extent identified in No. 9 below. We look at serviceability and safety, use a life-cycle cost analysis, and roll the results into the Capital plan. We use different criteria for roadways, bridges and tunnels in our evaluation. Currently, bridges are programmed through FHWA's Pontis program, tunnels use an MMIS system and Capital Plan, and pavements are under a Pavement Management System.

PANYNJ

PANYNJ is working to enhance their centralized asset management system. The goal is to track conditions and related structural information, e.g., original contract drawings, shop drawings, and repairs, as well as cost of inspections, repairs, etc.

The Authority is constrained by the Capital Budget and must make an objective case in order to get expenditures allocated for certain priorities.

VDOT

Currently, we are at a cross-road. We are developing a white paper on an asset management strategy. We currently have a pavement management system and a bridge management system, but no tunnel management system. We have an action item to place tunnels into a system.

WSDOT

Yes, there is an overall arching strategy mainly focusing on bridges and pavements.

9. If so, please identify the following as part of your asset management strategy.

CALTRANS

- *What are your overall asset management goals/objectives for your tunnels (i.e. Levels of Service; reliability, safety, security, quality of service, preservation)?*

  Three highest priorities are risk to the public, risk to the structure, and safety.

  For tunnels in a high traffic area on a major artery, such as leading into the urban area of District 4, keeping the tunnel open to traffic is the highest priority.

- *Are there established performance measures for each objective for particular systems in your tunnels? For example, a high number of accidents would indicate there are safety issues and safety related improvements would receive higher priority. What performance measures do you collect?*

  In urban area tunnels, closing the tunnel for even one hour can result in traffic back-ups for several miles. We typically try to perform short or emergency maintenance/repairs that can be achieved with very short closures during commute traffic and larger repairs that can be scheduled during off-peak traffic volumes. Also, the level of service assigned to bridges is also typical for tunnels. Our Districts maintains records of closures.

CDOT

- *What are your overall asset management goals/objectives for your tunnels (i.e. Levels of Service; reliability, safety, security, quality of service, preservation)?*

  Level of Service, reliability, safety, security.

- *Are there established performance measures for each objective for particular systems in your tunnels? For example, a high number of accidents would indicate there are safety issues and safety related improvements would receive higher priority. What performance measures do you collect?*

  On the major tunnels, improvements are determined through engineering inspections of the structures and integral systems and through evaluations by the assigned maintenance forces. We perform a survey of the major tunnels each year and submit the results to Headquarters. The survey results are tied to a letter grade (A, B, C, D, E and F), which are fairly subjective. Preservation actions follow a condition-driven budget. We collect a number of data for the large tunnels, which are maintained at the tunnel.

MassDOT

- *What are your overall asset management goals/objectives for your tunnels (i.e. Levels of Service; reliability, safety, security, quality of service, preservation)?*

  Each of these issues is weighted as decisions are made as to what to include in laying out the Capital Plan. Safety to the traveling public is always ranked highest, but traffic also weighs heavily on making the decisions.

- *Are there established performance measures for each objective for particular systems in your tunnels? For example, a high number of accidents would indicate there are safety issues and safety related improvements would receive higher priority. What performance measures do you collect?*

Performance measures vary from how quickly the Department responds to incidences to how quickly MassDOT processes invoices to contractors to all steps in between. In other words, we are measuring each step of our procedures to see where efficiency can be gained. Every accident is also tracked by video. The Department is anticipating adding a new position with the task to develop performance measures for the agency.

PANYNJ

- *What are your overall asset management goals/objectives for your tunnels (i.e. Levels of Service; reliability, safety, security, quality of service, preservation)?*

  The Authority deals with all issues stated, but places a special emphasis on transparency, as they are subjected to public scrutiny. This includes posting events to their website for crucial major repairs to keep the public informed.

- *Are there established performance measures for each objective for particular systems in your tunnels? For example, a high number of accidents would indicate there are safety issues and safety related improvements would receive higher priority. What performance measures do you collect?*

  Motor vehicle crashes at all Port Authority locations, including inside the tunnels, are monitored as part of the agency's data-driven Traffic Safety Improvement Program. Under this program, the goal is to identify and mitigate Priority Crash Locations to reduce crashes by 5% every year. If a high number of crashes are observed inside the tunnels, then a high priority is assigned to mitigate the crash problem through implementation of the appropriate engineering, enforcement, and/or education measures. One example may be the application of pavement treatments to increase the skid number and reduce skidding/wet roadway crashes.

  Traffic Engineering has integrated performance monitoring in its traffic asset management system, Roadway Devices Management System (RDMS). RDMS provides a strategic and systematic process of maintaining and upgrading traffic assets (signals, signs, pavement markings, etc.) effectively throughout their life-cycle by using a centralized asset repository, maintenance work management, key performance indicators and analysis reports.

  If complaints are registered from the public, they are sent to the Authority's front office, If required, the complaint is sent to the Facilities Department to address.

  The Authority also monitors noise levels for on-going construction contracts. They also use Customer Service Surveys for customer feedback. If there are more complaints, the issue is given a higher priority.

  Tunnels are only closed at nights from about 11:00 p.m. for approximately 5 hours for all work to be performed within the tunnels due to high ADT in each tunnel.

  If a large pavement project is scheduled, traffic studies will be performed and a Traffic Management Plan prepared in advance of any construction so that the public is informed of road closures, detours, alternate routes, etc.

VDOT

- *What are your overall asset management goals/objectives for your tunnels (i.e. Levels of Service; reliability, safety, security, quality of service, preservation)?*

Yes, safety takes the top priority; then, reliability to keep tunnels open is second. We try and keep tunnels open all the time. This is covered in VDOT's Business Plan (See Page 16) and is accessible by the link below.

http://www.virginiadot.org/about/resources/2013_VDOT_Business_Plan.pdf

- *Are there established performance measures for each objective for particular systems in your tunnels? For example, a high number of accidents would indicate there are safety issues and safety related improvements would receive higher priority. What performance measures do you collect?*

  Basically, we keep track of the number of accidents and number of vehicles that go through the tunnels (ADT). We keep records on performance of the lighting system and which lights are out, and the brightness of the lights for both day and night operations. We regularly wash the tunnel walls/lights and inspect interceptors, drains, and manhole covers. We have a grid group who are in charge of paving and asphalt. Asphalt roadway surfaces are replaced every ten years.

  As far as complaints, we receive very few of them. They are sent to operations when they come in. We haven't had any complaints at the Monitor and Merrimack Tunnel where all lighting was replaced in the last two years.

WSDOT

- *What are your overall asset management goals/objectives for your tunnels (i.e. Levels of Service; reliability, safety, security, quality of service, preservation)?*

  Safety is primary to ensure travelling public is safe; roadway quality is second; and, preservation of structural elements is third.

- *Are there established performance measures for each objective for particular systems in your tunnels? For example, a high number of accidents would indicate there are safety issues and safety related improvements would receive higher priority. What performance measures do you collect?*

  There are no formal performance measures although we do collect data such as ADT, roadway surface conditions (for input into the Pavement Management System), and accident data for evaluation of causes of the accidents. If primary structural elements are defined, and if they are determined to be in poor condition from a condition rating, then the agency would evaluate preservation actions. The agency does not use FHWA's Pontis program for bridges. They use their own Bridge Management System to determine what needs done. Map21 will require BMS data to be submitted rather than just NHI requirements. The agency has defined structural elements for both lined tunnels and unlined rock tunnels. They regularly shut down the rural northern unlined rock tunnels in winter due to ice accumulations from water seepage through the rock. Although there are no formal performance measures, they could mirror bridge performance measures as long as primary elements are defined.

<u>Prioritization of Tunnel Preservation Actions</u>

10	Are you using any particular tools to prioritize actions for repair, rehabilitation or replacement of systems in your tunnels? Please identify your tools.

CALTRANS

The only tools we have for the tunnel structure is FHWA's Pontis program. But, I am not sure how the program is being used to identify when these actions are required. The Districts do not use a particular tool to prioritize action. The main office makes recommendations to the District from inspection reports, and the District does their own prioritization.

CDOT

Inspections and maintenance forces perform a majority of the tasks except where outside resources are needed. We don't have specific tools. As tunnel superintendent with 35 years' experience, Mr. Salamon knows every system in the tunnel and knows the priority of what actions should be performed first. Safety issues are always addressed first.

MassDOT

Yes, we track everything through an MMIS system. This is our maintenance system that keeps track of our work orders and tells us when preventive maintenance needs to be completed. Our prioritization currently is based on our own judgment of the needs. We are still in the process of developing prioritization for safety, risks, etc.

PANYNJ

The Quality Assurance Division of the Port Authority of NY & NJ has developed Guidelines for Condition Surveys of Tunnels. The intent of the Guidelines is to provide a general methodology for assessing the structural condition of existing tunnels that are constructed of combinations of materials including concrete, cast iron, steel, and masonry and to prepare recommendations for repairs and/or rehabilitation. In addition, the Guidelines help to prioritize actions for repair, rehabilitation or replacement of systems in the tunnels. The Guidelines include a Repair Recommendation Matrix for determining repair recommendations for combinations of deficiencies such as cracks in concrete lining, cracks and/or corrosion of iron segments, missing bolts and leaks in concrete or segmental lining.

The Port Authority has developed a State of Good Repair (SGR) Index to prioritize projects to be implemented, due to limited funding. The information below summarizes factors considered to calculate the SGR Index. The index is based on the formula (Importance Index X Condition Index), which considers the following:

Importance Index:

- Life Safety
- Operational Impact
- Customer Service Impact
- Revenue Impact

Condition Index:

- Life-Cycle Criteria
- Serviceability
- Level of Maintenance Required
- Maintainability

Developed an internal formula for prioritization
Guidelines for Life-Cycle Cost Analysis
1 – 5 Rating or Life Safety Rating

VDOT

We just began using a computer maintenance management system (Micro Main) in the past year. The CMMS system generates work orders for performing preventive maintenance on the equipment. We received the system from our Transportation Operations center. We are in the process of inputting information into Micro Main.

VDOT performed a statewide tunnel risk assessment over the past year. This assessment focused on critical events that could result in closure of the tunnel, safety risk to users, and restoration costs. The assessment included development of risk mitigation strategies and programmed funding to implement these strategies.

WSDOT

Not generally. The major tunnels in the northwest region have maintenance tools that are used for mechanical/electrical systems. These tools are similar to MPET or a computerized maintenance management system (CMMS). The existing tools are also used for scheduling preventive maintenance.

11 What factors do you consider in prioritizing tunnel-related improvements? (Cost of repair, condition, usage/traffic, simplest improvements made first, etc.)

CALTRANS

Condition, risk and impact are the key factors with traffic as highest importance. However, if there is a serious issue that must be addressed, it is incumbent upon Headquarters to sell/market this issue to the District so that it receives the priority needed.

CDOT

For the major tunnels, those systems deemed critical to safe and reliable operation of the facility are the priority.

MassDOT

Safety, service, and then cost are our main focus areas, but the size of the project, complexity, and traffic management play a role as well. For example, we have a roadway slab replacement project in the Calahan Tunnel which will require a shut down for three months to complete. For something this complex, we must go through all levels of the Authority for authorizing the work, plus provide an extensive outreach campaign for the public.

PANYNJ

See explanation in Paragraph 10.

VDOT

All the above.

Critical Assets – Ventilation Systems, Tunnel Drainage, Power Distribution, Traffic Management, Fire Suppression.

WSDOT

Typically, repairs are based on condition. For one rural tunnel that was timber lined, the tunnel had considerable timber damage and an evaluation was made to either replace all the timber or encase it with shotcrete. The structural aspect is critical as it relates to the safety of travelers. For the timber-lined tunnel, repairs were made in five stages, four of which are complete as of this date. Safety of the public is the highest importance. Most tunnel repairs have been minor to this point. We have some tunnels in Seattle area that should have mechanical-electrical upgrades, but this is put off due to costs, although minor, less costly repairs are made. Other factors include cost, obsolescence and criticality.

12. How is your prioritization affected by the need to group preservation actions within a given tunnel to effect improvements at the same time to reduce tunnel traffic impacts? For example, do you prioritize individual improvements across the entire tunnel system or prioritize the tunnel to be improved?

CALTRANS

The Districts receive the lists of repairs to be addressed from the inspection reports delivered from Headquarters. It is their responsibility to group repairs into a contract or multiple contracts in order to accomplish the repairs. Prioritization is within one tunnel, but may expand to adjacent tunnels if they are in proximity to each other. For example, one major lighting contract had a contract with five tunnels for work progressing simultaneously in the tunnels. Another project was to repair 50 motors, but all within one district. The issue usually comes down to an administrative issue with the District.

CDOT

We have six distinct regions statewide in Colorado, and each one of those six regions has their own budget for tunnels in that region. It will be dealt with regionally rather than on a state level. Surveys of the structure and equipment are only done at the two major tunnels, and are assigned a letter score of A through F for each element included. Surveys are typically based on Mr. Salamon’s knowledge of the element for assigning a rating score.

MassDOT

We look at the tunnel as a whole and prioritize for the overall benefit of operation of the tunnel. We weigh the pros and cons for each preservation action.

PANYNJ

For prioritization, work is coordinated between the two tunnels – Holland and Lincoln. It is easier to close one tube of the Lincoln Tunnel for maintenance/repairs as two tubes will be open for traffic access. It is harder to close a tube in the Holland Tunnel due to traffic volumes. When it is necessary, the public is warned to consider taking other routes. When a particular tunnel tube is closed, work will include both priority and routine repairs/maintenance. Currently, there are two construction jobs at Lincoln Tunnel which requires working in all three tubes. However, closures are coordinated between the tubes to keep traffic flowing.

VDOT

The primary concern is the hours of closures due to traffic backups. For the Hampton Roads and Monitor Merrimack Tunnels, which handle about 100,000 cars per day, it not unusual to see 2, 3, or 4 mile backups in the morning and then the reverse in the afternoon for normal operations. We will program preventive maintenance or preservation actions based on number of hours available for work in the tunnel. When the tunnel in an urban area is shut down for a period of up to two weeks during any month (one week in each tube and only closing one lane at a time), we will perform work on the lighting, interceptors, pumps, trash removal, washing, cleaning tanks for outfall ratings, etc. Typically, drains are cleaned every 1 ½ months. While this is being accomplished traffic is routed through the other tube of the adjacent tunnel.

WSDOT

We prioritize the actions that we know across all tunnels in the state and do these actions first. We are getting away from the "do it all while you're there" action because we don't have sufficient funds for repairing all deficiencies. We do what only needs to be done and then defer the rest of the preservation actions to Maintenance. All decisions are made from the centrally-based bridge office instead of at the regional divisions.

13. If you could utilize a tool to assist in prioritizing tunnel preservation actions, what would be the critical characteristics of the tool in order to make it most useful for your agency (i.e. use of Excel or other software, ease of use, tailored to meet overall agency objectives, etc.)?

CALTRANS

Any software that you develop should be considered applicable to a wireless tablet, I-phone, or GPS unit. Any database should be interactive. The goal would be to eliminate paper reports. Caltrans is advancing in the highly urban District 4 by proposing to build a TMC (Tunnel Maintenance Center) that will house all data for all 12 tunnels in District 4. By doing this and having software available in this center should make prioritizing of preservation actions more efficiently done.

It feels that structure maintenance would not be interested in any tool except Pontis, since they consider the tunnel as just another one of the many 26,000 bridge projects where preservation actions are required. He feels a better tool would be to help prioritize and schedule preventative maintenance work.

CDOT

Easy-to-use software that accounts for Levels of Service from a condition perspective.

MassDOT

User friendly for the field personal to use in the field to report what is completed or what needs corrective work. Work orders through our MMIS are written down and submitted to someone else to enter the data into the system. A software application which could also be used by field personnel to enter information directly would be helpful. We are in the early stages of trying to implement Maximo by entering field data, such as catch basins currently.

PANYNJ

Tool could be an Excel Spreadsheet used as a Guide, but not to provide an overall priority ranking. Although not foolproof, actions should be weighted, and considerations given as to how revenues are affected. The Authority's priorities are generally maintenance and not the amount of revenue generated.

A key characteristic of this user friendly tool would be the ability to generate a prioritized list of state of good repair projects based on key asset data such as remaining asset life and replacement cost. The traffic engineering asset management system, RDMS currently generates asset life-cycle reports by employing a specialized enterprise data reporting software which provides both flexibility and ease-of-use.

VDOT

An RFP for Asset Management for all of VDOT is currently being drafted, but is not authorized yet. It may take 3 to 4 years for such authorization. In the interim period, we are maintaining records in an Excel spreadsheet.

Preservation actions for both construction and maintenance are included in the 6-year Capital Improvement Plan.

WSDOT

We would have to mirror or parallel what we do with bridge inspection elements. We would recommend a simple rating system be used to categorize deficiencies, such as good, fair, or poor ratings. A pass/fail system might even be employed for mechanical/electrical equipment. We currently use Microsoft Access so would prefer that any tool interact with Microsoft products. All tunnel elements need to be clearly defined. Tunnel inspections are now considered a safety inspection as we are not using the NBI coding as we do for bridges. We would have both consultants and the in-house staff to outline details for the inspections. We generally rely on consultant services for M/E inspection, to include inspections of fans, vibration measurements, etc. Other in-house groups perform basic M/E preventive maintenance and regular oil checking.

Funding

14 How does your agency distribute funding between tunnels and other highway assets? Does the distribution of funding change from year to year?

CALTRANS

There is no distribution of funds for the tunnel structure since it is wrapped together with bridges. For maintenance efforts, each District has their own funding budget given to them. The interviewee was not aware how the budgets are allocated.

CDOT

On the two major tunnels, funding levels vary from year to year depending on budget funds available, level of service goals, Department priorities, and the previous year's expenditures. Tunnels are separate from bridges.

MassDOT

The Tunnel for the most part is funded by tolls collected at the tunnels whereas other highways are state funded. Each is separate and one does not affect the other.

PANYNJ

Twelve percent is included in the 2012 capital plan for tunnels (i.e., the Holland and Lincoln Tunnels). Yes, funding changes from year to year.

VDOT

Funding is fairly consistent from year-to-year. We request an amount for maintenance costs per year for each Tunnel. The Operations group reviews the budget and then decides how much to expend per year. We must lobby for major repairs over a 6-year period; these are included in the capital plan.

WSDOT

Definitely, we are in a downturn as far as funding goes. It changes from year to year. It's going to be a big challenge in the future. We have different subcategories in the bridge program for different types of work, i.e. painting and miscellaneous (all structures <20', such as sign structures, culverts and tunnels). Only performed preservation actions in one tunnel in last 10 years since the many tunnels in Seattle are new.

15. How do funding limitations affect your tunnel preservation actions?

CALTRANS

The Districts program what fits into their overall budget allocated. But, if there is an emergency need, a request can be made to cover the preservation action with an emergency contract.

CDOT

Moderately as preservation actions provide an advance warning as to what will be required in the future. Both major tunnels are high profile tunnels, and absorb 90% of funds expended on tunnels. These tunnels have the highest ADT, are on I-70, and have greatest interest from the Transportation Commission for maintaining them to be operational. The Commission will usually find the necessary dollars to perform the preservation actions needed.

MassDOT

The cash flow of tolls is what affects it. For example if a project cost $500M, then we need to plan to hold two years of toll money to advertise since tunnel tolls generate about $300 million per year. This is laid out in our capital plan.

PANYNJ

Preservation actions may be delayed and included in capital expenditures as part of the capital plan.

VDOT

VDOT spreads them out over a 6-year plan.

WSDOT

We defer some of the actual actions.

16 How do you determine number of staff needed for tunnel maintenance and preservation?

CALTRANS

We currently have 38 tunnels throughout California. All staff comes from the total staff of over 22,000 employees in Caltrans. There is sufficient staff to cover any issue.

CDOT

For the major tunnels, operational staffing was established analyzing safety criteria such as emergency and fire response on a 24/7 schedule. Special crews (electrical, electronic, etc.) are based on historical workloads. When major repairs are needed, consultants and contractors are engaged to oversee and accomplish the repair, respectively. This would include major electrical repairs or a major break in a water line. The DOT does provide its own fire training.

MassDOT

We are working through this process now by looking at the work output levels per employee for each task since all tunnels are within a 27-mile radius. Maintenance personnel are dispersed from a centralized location to each tunnel as needed. We use performance measures to establish the number of personnel needed based upon tasks to be completed each day. We have a total of 416 people to support our tunnel needs in two major shifts, which includes administrative support and toll booth operators. We are working to determine how long each employee should take to perform a certain task so that we can ultimately determine the number of personnel required for all tunnel operations. Typically, we have four to five lanes per tunnel closed down each night. This could include 3 right lanes and 2 left lanes each night. There are times when we have a 1-month shut down of an entire bore in a tunnel so that many functions can be accomplished simultaneously. We will often have between 110-120 people performing maintenance or repair work such as electrical, communication, painting lines, washing signs, etc. during a full bore shut down. Hours for shut downs vary, but typically occur between 3:30 p.m. to 5:00 a.m. time period.

PANYNJ

Limited maintenance personnel at the facilities to perform Preventive Maintenance; often staff needs assistance on several items requiring maintenance. If an engineering solution is required, typically go to outside consultants to design the solution.

VDOT

In most cases, both routine maintenance designs and construction funding are done by a third party – outside consultants. Depending on level of input to put a project together, we may use internal staff for smaller design projects. We may have an old contract that worked well and we may use that contract again for this work. VDOT is currently undertaking a study to determine how many people are required by operations and maintenance to meet their needs.

For the Eastern Region tunnels, 22 people maintain the tunnels; 50% are from VDOT and 50% from contractors. Total overall maintenance and operations personnel available for tunnels are about 200 people.

WSDOT

We have sufficient staff (about 7,000) within WSDOT to handle our design and construction program. If a special need (mechanical/electrical) arises, we engage consultants to develop the plans and use in-house staff to review the design. Maintenance staff is determined by historical needs.

17. How is your staffing for tunnel maintenance and preservation affected by varying levels of funding?

CALTRANS

We don’t have particular number of personnel assigned to tunnels only. Maintenance contract – that gets absorbed by the bridge design staff. From a maintenance aspect, we realize that we have to increase tunnel maintenance because the level of maintenance activities has increased in the last 10 years.

We have 3 to 4 new tunnels under construction currently. We are considering developing an organization specifically for tunnels. We have instituted a committee to take care of the tunnel structure, and we are building a Traffic Management Center to better program maintenance and repairs when there are several tunnels in close proximity.

CDOT

Unaffected. Staff is set from year to year.

MassDOT

Not by the funds, but more by the overall full-time equivalent employees for our entire DOT. This limits how many employees I can hire. The funding levels for the staff to purchase and do the maintenance needed seems to be fine, we just need the employees to reach the output needed.

PANYNJ

Fairly consistent from year-to-year, although have experienced funding level decreases in the past.

Labor costs are increasing with time, but there is no increase in overall yearly budget. This affects how critical systems in tunnel are maintained. The Authority is relying more on consultants for engineering solutions.

VDOT

Yes, but funding from VDOT's overall program will affect the number of hires.

WSDOT

The tunnels are a minor part of the overall bridge program. Maintenance must present a story of the tunnel needs to get them addressed. However, we are falling behind in addressing needs and have added additional resources internally. Staff needs have been reduced as crews become more productive with new technology.

18. How do you determine the funding needed for tunnel preservation actions (i.e. internal estimate, engineer's estimate, etc.)?

CALTRANS

We use internal estimates that were created as part of performing an advanced planning study (APS). Then, funding will follow based on the study.

CDOT

For the major tunnels and major projects, consultant engineering estimates are requested, but are evaluated by internal staff. For other less critical repairs, internal engineering estimates are used to set funding levels.

MassDOT

Engineers estimate and then when the bids come in, we continuously update the capital plan. Can be either internal or external estimates. Depends on who does the design of the repairs. Capital plan numbers are provided from internal staff.

PANYNJ

For early planning actions, develop a Performa number as an anticipated expenditure. As the level of design advance, modify the preservation actions estimate of costs accordingly to the level of design completed. Studies are performed in-house, but designs are performed by consultants. The Authority's Chief Estimator and his staff review the engineer's estimates and program the cost based on their best estimate and knowledge of prior work performed. All unit cost items are provided by internal staff.

VDOT

We do it both ways – use both internal and external personnel.

WSDOT

Depends on the element we are talking about. If tunnel lining or shotcrete is needed, we use internal estimates to determine which method to pursue. If mechanical/electrical work is required, we use consultants to generate repair estimates and then compare to other state data

19. Other Information Provided

PANYNJ

Port Authority of NY & NJ – Tunnels, Bridges and Terminals (TB&T)

<u>Maintenance Program</u>: Managing existing assets through an effective ongoing program of preventive maintenance, coupled with capabilities for corrective and emergency repairs.

The program is designed to ensure availability of critical infrastructure and systems and to advance prudent life-cycle economics. This program is responsible for all aspects of day-to-day maintenance at the facilities, including oversight and planning of maintenance crafts and schedules, asset inventories, maintenance routines consistent with original equipment manufacturers' recommendations, construction contractor coordination, balanced resource plans (i.e., staffing levels, overtime, contracts), service contract management, and overall facility conditions and appearance. Outcomes of this program include critical asset and system availability, completion of maintenance routines within departmental and agency standards, minimizing the effect of closures on customers, and customer satisfaction.

<u>Asset Management Program</u> - Managing the preservation of existing assets through inspection, maintenance, and rehabilitation initiatives to extend useful life, comply with structural standards, and recognize life-cycle economics.

The program also provides for program management of new and replacement assets, and for the handling of all of the Department's technical initiatives including immediate response to emergencies at facilities, facility troubleshooting, response to outside entities, and provision of patron service improvements handled by tenant alterations. The major components of the Asset Management Program include the management of current capital projects, development of a long-term Capital Program, coordination of the Operating Major Work Program, oversight of the Structural Integrity and Inspection Program, coordinating with the Engineering Services Program, management of Contract Services Program, and coordination of asset reliability activities with information systems. Outcomes of this program include the installation of new facility infrastructure, extension of existing asset service life, compliance of structures with appropriate standards, immediate responsiveness during emergency conditions, delivery of prompt remedial action plans, completion of regular asset condition assessments, minimal facility interruptions from maintenance and emergency repairs, and improved customer service.

APPENDIX C

Catalog of Preservation Actions

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 closed-circuit TV (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		

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 Standpipes												
Fire Department Connections Capped and Clear				X					X			
Confirm threads are undamaged and caps in place				X					X			
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’s 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			

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
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		
Fire Pumps												
Visually inspect fire pump		X							X			
Operate pump – (Non-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			

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 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			
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	
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**
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		
Clean all smoke and heat detector housings and check battery voltage under load					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
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			

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
Tenable Environment (Note: Smoke Control Ventilation is located in Fire Suppression Section)		X							X		X	
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 update periodically					X				X		X	
Tunnel Personnel Training of execution of ERP			X						X		X	
Training Exercises with Participating Agencies						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
Hydrocarbon Detector												
Confirm Hydrocarbon Detector will initiate both local and remote alarms								X	X			
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 all safety guards and covers (belt, chain, electrical panel) in place and secure.		X							X		X	
Verify that no plastic (PVC, CPVC) pipe located in supply air passages.					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
Verify all batteries properly stored and vented. Confirm battery charging only taking place in well ventilated spaces.		X							X		X	
Verify flammable material stored in proper containers and properly ventilated spaces.		X							X		X	
Verify secondary containment 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			

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After power shutdown, clean entire switchgear interior								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			
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			

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Lubricate and verify operation of all mechanisms								X	X			
Apply current equal to 90 to 110 percent 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			
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			

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Apply current equal to 300 percent 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 any adjustments if necessary								X	X			
Lubricate bearings, links, pins, and cams								X	X			
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 one minute using a test voltage of 1,000 volts Direct Current (DC). Compare results with previous tests.								X	X			

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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			
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			

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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			
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			

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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, overspeed, and other features				X					X			
Perform vibration base-line 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			

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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			
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			

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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			
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			

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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 percent and 600 percent of rating against the tripping curve								X	X			
Test all alarm and lights for proper feedback from devices						X			X			

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Perform calibration test and verify proper operation of all meters								X	X			
Replace ventilation fan starters with 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 alarm and lights for proper feedback from devices						X			X			

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Check all connections for tightness						X			X			
Clean cabinets						X			X			
Replace Computer (HMI) Hardware								X				X
Upgrade Control System Software								X				X
Backup Control System Programs								X				X
Tunnel Vehicle Over-height System												
Check for proper operation of overheight 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 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			

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Verify Operation of portal light meters				X					X			
Verify operation of time clocks				X					X			
Perform group relamping for specific lamp types						X						X
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		

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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 AHJ.						X			X		X	
Air Conditioning Unit												
Clean or replace air filters				X					X			
Check coils and clean if necessary						X			X			

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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			
Test relief valve or safety valve (use extreme caution)						X			X			
Check all steam traps for operation, leak through			X						X			

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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 AHJ.						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 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			
Check all wires and power connections for tightness						X			X			

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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 (ATC/BAS)												
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			

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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			

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Drainage System (Roadway)												
Grate inspection (damage, blockage)			X							X		
Flush inlet and piping system					X				X			
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			

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Emergency Generator												
Generator exercised.			X						X			
Fuel lines inspected for leakage.			X						X			
Fuel filter changed.						X			X			
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	

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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			
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			

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Check oil level in chain drive enclosures (as applicable). Confirm breather vent is open	X								X			
Cleaning of 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 percent 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			
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 and adjust if necessary			X						X			
Perform oil analysis by testing laboratory 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, and lubricate if necessary				X					X			

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Dampers (Tunnel Ventilation)												
Operate motor-operated dampers and listen 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 debris as necessary.			X							X		
Fuel Oil Day Tank												
Inspect tank for damage, corrosion, or leakage on both inside and outside of tank. 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			

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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, equipment supports, and associated equipment. Repair corrosion damage, properly prepare surface and repaint equipment as required.				X								X
Check for missing or loose mounting hardware and fastener. Re-torque or replace fasteners as necessary.				X						X		
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			

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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		

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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		

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
Tighten the fan guard, motor frame, and fan bolts, and check fan clearances						X			X			
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 (VFDs)												
Verify environmental conditions required by unit manufacturer are being met by equipment room HVAC equipment (typically 50-104 degrees F)	X								X			
Verify cooling air screens and passageways are clean and unobstructed.		X							X			

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
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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	
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 water 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	

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
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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		
Remove Icicles Above Travel Roadway	X								X			
Replace Damaged or Deteriorated Timbers in Timber-lined Tunnels												X

Preservation Action Item Procedure Description	Type											
	Preservation Service Interval								Other			
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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		