# Best Practices For Roadway Tunnel Design, Construction, Maintenance, Inspection, And Operations



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# Best Practices For Roadway Tunnel Design, Construction, Maintenance, Inspection, And Operations

*Supported by the*
National Cooperative Highway Research Program

April 2011

The information contained in this report was prepared as part of NCHRP Project 20 68A U.S. Domestic Scan, National Cooperative Highway Research Program.

**SPECIAL NOTE:** This report IS **NOT** an official publication of the National Cooperative Highway Research Program, Transportation Research Board, National Research Council, or The National Academies.


CERESOLA
WARNING

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The purpose of each scan and of Project 20-68A as a whole is to accelerate beneficial innovation by facilitating information sharing and technology exchange among the states and other transportation agencies, and identifying actionable items of common interest. Experience has shown that personal contact with new ideas and their application is a particularly valuable means for such sharing and exchange. A scan entails peer-to-peer discussions between practitioners who have implemented new practices and others who are able to disseminate knowledge of these new practices and their possible benefits to a broad audience of other users. Each scan addresses a single technical topic selected by AASHTO and the NCHRP 20-68A Project Panel. Further information on the NCHRP 20-68A U.S. Domestic Scan program is available at http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=1570.

This report was prepared by the scan team for Scan 09 05, *Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection, and Operations*, whose members are listed below. Scan planning and logistics are managed by Arora and Associates, P.C.; Harry Capers is the Principal Investigator. NCHRP Project 20 68A is guided by a technical project panel and managed by Andrew C. Lemer, Ph.D., NCHRP Senior Program Officer.

**Kevin Thompson, P.E.,** *Caltrans, AASHTO Co-Chair*

**Jesus Rohena, P.E.,** *FHWA, FHWA Co-Chair*

**Alexander K. Bardow, P.E.,** *Massachusetts DOT*

**Barry B. Brecto, P.E.,** *FHWA Washington State Division*

**Bijan Khaleghi, Ph.D.,** *P.E., S.E., Washington State DOT*

**Louis Ruzzi, P.E.,** *Pennsylvania DOT*

**Michael G. Salamon,** *Colorado DOT*

**Fulvio Tonon, Ph.D., P.E.,** *Liaison, TRB Tunnels and Underground Structures Committee*

**Mary Lou Ralls, P.E.,** *Report Facilitator*

## Disclaimer

# Scan 09-05

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**REQUESTED BY THE**

**American Association of State Highway and Transportation Officials**

**PREPARED BY**


**Kevin Thompson,** P.E.,
*Caltrans, AASHTO Co Chair*

**Jesus Rohena,** P.E.,
*FHWA, FHWA Co Chair*

**Alexander K. Bardow,** P.E.,
*Massachusetts DOT*

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*Pennsylvania DOT*

**Michael G. Salamon,**
*Colorado DOT*

**Fulvio Tonon,** Ph.D., P.E.,
*Liaison, TRB Tunnels and Underground Structures Committee*

**Mary Lou Ralls,** P.E.,
*Report Facilitator*


**SCAN MANAGEMENT**


**Arora and Associates, P.C.**
**Lawrenceville, NJ**

**April 2011**



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# Table of Contents

# List of Appendices

# List of Figures

# Acronyms

| | |
|---|---|
| **AASHTO** | American Association of State Highway and Transportation Officials |
| **ACI** | American Concrete Institute |
| **ADA** | Americans with Disabilities Act |
| **ADECO** | Analysis of Controlled Deformations tunneling method |
| **ADT** | Average Daily Traffic |
| **AFF60** | Tunnels and Underground Structures Committee (Transportation Research Board) |
| **ANSI** | American National Standards Institute |
| **ASCE** | American Society of Civil Engineers |
| **ASME** | American Society of Mechanical Engineers |
| **ASTM** | American Society for Testing and Materials |
| **BMS** | Bridge Management System |
| **AWV** | Alaska Way Viaduct (WSDOT) |
| **CA/T** | Central Artery/Tunnel |
| **CBBT** | Chesapeake Bay Bridge Tunnel (Virginia) |
| **CCTV** | Closed Circuit Television |
| **CEE** | Construction Earthquake Evaluation |
| **CEM** | Continuous Emissions Monitoring Program |
| **CFM** | Cubic Feet per Minute |
| **CFR** | Code of Federal Regulations |
| **CO** | Carbon Monoxide |
| **DEP** | Department of Environmental Protection |
| **DOT** | Department of Transportation |
| **EJMT** | Eisenhower/Johnson Memorial Tunnel (Colorado) |
| **EPA** | Environmental Protection Agency (U.S.) |
| **FEE** | Functional Earthquake Evaluation |
| **FHWA** | Federal Highway Administration |

| | |
|---|---|
| **FTA** | Federal Transit Administration |
| **GPR** | Ground Penetrating Radar |
| **HAR** | Highway Advisory Radio |
| **HLT** | Hanging Lake Tunnel (Colorado) |
| **HOC** | Highway Operations Center |
| **HPS** | High Pressure Sodium |
| **HRBT** | Hampton Roads Bridge Tunnel (Virginia) |
| **IESNA** | Illuminating Engineering Society of North America |
| **IPCS** | Integrated Project Control System |
| **IRT** | Infrared Thermography |
| **ITS** | Intelligent Transportation Systems |
| **LED** | Light Emitting Diode |
| **LPS** | Low Pressure Sodium |
| **LRFD** | Load and Resistance Factor Design (AASHTO) |
| **M&E** | Mechanical and Electrical |
| **MassDOT** | Massachusetts Department of Transportation |
| **MDE** | Maximum Design Earthquake (Port Authority of NY&NJ) |
| **MMIS** | Maintenance Management Information System |
| **MMMBT** | Monitor Merrimac Memorial Bridge Tunnel (Virginia) |
| **NATM** | New Austrian Tunneling Method (aka Sequential Excavation Method) |
| **NBI** | National Bridge Inventory |
| **NBIS** | National Bridge Inspection Standards |
| **NCHRP** | National Cooperative Highway Research Program |
| **NEC** | National Electrical Code |
| **NEMA** | National Electrical Manufacturers Association |
| **NFPA** | National Fire Protection Association |
| **NFPA 502** | Standard for Road Tunnels, Bridges, and Other Limited Access Highways |

| | |
|---|---|
| **NOx** | Nitrogen Oxides |
| **OMC** | Operations, Maintenance, and Control Building (Caltrans) |
| **OSHA** | U.S. Occupational Safety and Health Administration |
| **PANY&NJ** | Port Authority of New York and New Jersey |
| **PennDOT** | Pennsylvania DOT |
| **PLC** | Programmable logic controller |
| **PM** | Particulate Matter |
| **PM 10** | Particulate Matter Standard That Includes Particles with a Diameter of 10 Micrometers or Less |
| **PTC** | Pennsylvania Turnpike Commission |
| **RCT** | Reverse Curve Tunnel (Colorado DOT) |
| **SCADA** | Supervisory Control and Data Acquisition |
| **SCOBS** | Highway Subcommittee on Bridges and Structures (AASHTO) |
| **SEE** | Safety earthquake evaluation |
| **SEM** | Sequential Excavation Method (aka New Austrian Tunneling Method) |
| **SM&I** | Structure Maintenance & Investigations (Caltrans) |
| **T 20** | AASHTO SCOBS Technical Committee for Tunnels |
| **TBM** | Tunnel boring machine |
| **TMC** | Traffic Management Center |
| **TMS** | Tunnel Management System |
| **TRB** | Transportation Research Board |
| **UPS** | Uninterruptible power supply |
| **VDOT** | Virginia Department of Transportation |
| **VHF** | Very High Frequency (30 to 300 Megahertz) |
| **VMS** | Variable Message Sign |
| **WSDOT** | Washington State DOT |

# Executive Summary

## Introduction

Most highway facility components in the United States are governed by design, construction, maintenance, inspection, and operations codes and regulations of the American Association of State Highway and Transportation Officials (AASHTO) and the U.S. Federal Highway Administration (FHWA). However, to date, highway tunnels in the U.S. do not have comparable national codes and regulations. Recent events, such as the July 2006 ceiling collapse of the I-90 Central Artery/Tunnel (CA/T) in Boston, Massachusetts, have called attention to the need for such national standards.

After investigating the CA/T ceiling collapse, the National Transportation Safety Board (NTSB) recommended that the FHWA seek legislation to establish a mandatory tunnel inspection program that would identify critical inspection elements and specify an appropriate inspection frequency. The FHWA requested clearance from the Office of the Secretary of Transportation to proceed with regulatory action to develop National Tunnel Inspection Standards similar to the National Bridge Inspection Standards (NBIS) contained in the Code of Federal Regulations, 23 CFR 650, Subpart C.

An Advance Notice of Proposed Rulemaking was published in the Federal Register in November 2008. In July 2010, a Notice of Proposed Rulemaking that addressed comments received on the ANPRM was published in the Federal Register. As of the writing of this report, FHWA is preparing a Final Rule to address comments received on the NPRM.

## Scan Purpose and Scope

Domestic Scan 09 05, *Best Practices for Roadway Tunnel Design, Construction, Maintenance, Inspection, and Operations*, conducted during August and September 2009, is one of the activities initiated to assist in addressing the need for national tunnel standards and a national tunnel inventory. The nine member team consisted of two representatives from FHWA, five representatives from state Departments of Transportation (DOTs), an academic member representing the Transportation Research Board (TRB) Tunnels and Underground Structures Committee (AFF60), and the report facilitator.

The team selected scan hosts that have significant tunnels in their inventories and use innovative approaches; agencies with ongoing or upcoming tunnel construction projects were also of interest. Hosts along the East Coast were the Chesapeake Bay Bridge and Tunnel (CBBT) District, the Massachusetts Turnpike Authority[1], the Port Authority of New York and New Jersey, and the Virginia DOT. Hosts in the western U.S. were the California DOT (Caltrans), the Colorado DOT,

[1] The Massachusetts Turnpike Authority became part of the Massachusetts DOT (MassDOT) effective November 1, 2009.

the Washington State DOT, the City of Seattle (DOT and Fire Department), and the Seattle Sound Transit System. In addition to site visits with scan hosts, the team held Web conferences with representatives from the Alaska DOT, the District of Columbia DOT, and the Pennsylvania DOT.

The scan team investigated tunnels that are part of the state, regional, and local highway systems. While the scan's scope was roadway tunnels, the team also visited the Seattle Transit System.

The scan's focus was inventory criteria used by highway tunnel owners; highway tunnel design and construction standards practiced by state DOTs and other tunnel owners; maintenance and inspection practices; operations, including safety, as related to emergency response capability; and specialized tunnel technologies. The scan also included consideration of fire suppression; traffic management; incident detection and management; and analysis, design, and construction repairs of existing tunnels.

General topics of interest to the scan team were:

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

## Summary of Findings and Recommendations

The scan team identified a number of highway tunnel initiatives and practices of interest for nationwide implementation or for further evaluation for potential nationwide implementation, as listed below.

### 1. Develop standards, guidance, and best practices for roadway tunnels.

Design criteria for new roadway tunnels should consider:

- Performance-based construction specifications
- Design recommendations for extreme events (manmade and natural [e.g., seismic and storm events]) and tunnel security (e.g., blast resistance and lifeline requirements[2])
- Design criteria for vertical clearance, horizontal clearance, and sight distance
- Criteria for tunnel design life and future maintenance for structural, mechanical, electrical, and electronic systems
- Criteria for new tunnel load rating

[2] Lifeline requirements, which can vary among agencies, recognize the need for certain routes and key facilities, such as bridges and tunnels, to be operational immediately or shortly after a major incident or event, such as an earthquake.

- Seismic design criteria for one-level versus two-level design events
- Americans with Disabilities Act (ADA) requirements for emergency egress[3]
- Placement and layout of the tunnel operations center
- Fire and life-safety systems in tunnels

Rehabilitation of existing tunnels should consider obsolescence, tunnel design life, high performance materials, and existing geometry to maximize safety, system operation, and capacity.

Tunnel systems are generally complex and expensive in terms of capital costs. It is critical that any emergency response plan includes the basis of design for how the structure and systems were designed to operate; without this information, the response plan may be incorrect. The use of peer review teams and technical advisory panels with subject matter expertise should be considered in developing site specific criteria. Risk management of complex systems is important, as is system redundancy. The Supervisory Control and Data Acquisition (SCADA) system can be programmed to monitor and control redundant systems and structures

Contract guidelines for roadway tunnels need to be developed to accommodate the various procurement methods (e.g., design bid build, design-build, and design-build operate finance), considering to the extent applicable the Underground Construction Association's *Recommended Contract Practices for Underground Construction.*

Design and construction standards and guidelines need to be developed for tunnel construction methods, such as the use of tunnel boring machines (TBMs) versus conventional tunneling, design criteria that include seismic design, and lifeline requirements. Conventional tunneling methods include the Sequential Excavation Method (SEM) or New Austrian Tunneling Method (NATM), the analysis of controlled deformations (ADECO) method, and the cut-and-cover method.

Some of the above topics will be addressed in a National Cooperative Highway Research Program (NCHRP) project that began in 2010 and is sponsored by the AASHTO Subcommittee on Bridges and Structures to develop Load and Resistance Factor Design (LRFD) specifications and guidance for new and existing tunnels.

## 2. Develop an emergency response system plan unique to each facility which takes into account human behavior, facility ventilation, and fire mitigation.

A fire ventilation study should be performed and a fire ventilation plan developed and adopted for each facility. To adequately address emergencies, a tunnel's design should take into account the realistic spread of fire, smoke, toxic gases, and heat in the tunnel and the effect of different

[3] The ADA does not currently apply to tunnels.

types of ventilation systems on the fire, including fire suppression, if the tunnel is so equipped. Fire mitigation should include spill control.

In general, the scan team found that facilities should improve their procedures to direct the public to safety. The fire plan should be consistent with the motorists' various responses to a fire, and the operation of all tunnel fire response systems should be consistent with this behavior. Enhancements to direct the public to safety (e.g., better signage and intelligible public address systems) should be considered, including the recommendations for these that were made in the 2005 international tunnels scan[4].

Further research is needed to understand how fire and smoke spread in a tunnel and how people react in emergencies. The scan team recommends that the research topics related to fire that were developed during the AASHTO workshop on tunnel safety and security research needs (November 2007, Irvine, California) should be considered.

## 3. Develop and share inspection practices among tunnel owners

The scan team found that the best tunnel inspection programs have been developed from bridge inspection programs. In many cases, bridge inspectors also perform the structural inspection of tunnels. Therefore, the team recommends that tunnel inspection programs be as similar as possible to bridge inspection programs.

Those components of the tunnel that carry or affect traffic (e.g., roadway slabs and floor systems that carry traffic) should be load rated in accordance with the AASHTO *Manual for Bridge Evaluation* to the extent possible. In the analyses, different operational conditions should be considered. Structural analyses should be performed on non-traffic-carrying components (e.g., plenums, plenum walls, and hangers) as their physical conditions change, as they are modified, and as the loads that they are to be subjected to change (e.g., air forces if fans are upgraded).

Recommended practices for inspection frequencies, minimum code requirements, and a federal coding manual need to be developed. Current practice is a frequency of one to five years for structural inspections and daily to yearly frequencies for mechanical and electrical (M&E) inspections, depending on the level of inspection. Maximum frequencies should be set, and owners should be encouraged to develop actual frequencies based on manufacturer requirements and a risk-based analysis of hazards due to condition, deterioration, and performance history. If the inspection frequency is less than accepted best practices and standards, the owner will take on liability. Inspection frequency should be based at least partially upon the level of risk.

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[4] Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response, U.S. DOT FHWA in cooperation with AASHTO and NCHRP, 2005, http://international.fhwa.dot.gov/links/pub_details.cfm?id=494

A baseline data inventory for tunnels needs to be developed for submission to the FHWA in conjunction with NCHRP 20-07/Task 261 (Best Practices for Implementing Quality Control and. Quality Assurance for Tunnel Inspection), Task 4.

Inspection practices need to be shared among tunnel owners in five areas:

1. The scan team identified a best practice for the inspection of submerged tunnels using multi-beam sonar scans.
2. Tunnel inspection training that takes into consideration all aspects of the tunnel structure and systems needs to be developed.
3. Tools to find voids behind tunnel linings need to be developed..
4. Coordinated overnight tunnel closing should be done so that as much maintenance and inspection as is possible can be done.
5. Best inspection practices should be shared

## 4. Consider inspection and maintenance operations during the design stage.

The scan team found that inviting all disciplines to provide their input during the design phase results in a better product. The design of a tunnel should address future inspection and maintenance of all tunnel systems and equipment by providing for adequate, safe, and unimpeded access to all components. This can be accomplished by bringing together all engineering disciplines that will be accommodated in the tunnel. While the scan team understands that tradeoffs must be made between access and a practical design, these tradeoffs could have cost and safety implications for maintenance and inspection over the life of the tunnel.

## 5. Develop site specific plans for the safe and efficient operation of roadway tunnels

A concise site specific tunnel operations manual needs to be developed. It should include the design assumptions for fires and other hazards, ventilation procedures, traffic control guidelines, and general maintenance procedures (e.g., washing guidelines and fan and bearing maintenance). The manual should also include training guidelines and training schedules for all personnel and should reference the incident response manual for incident response procedures and training.

Tunnel owners should implement state-of-the-art video surveillance and communication systems, which provide numerous benefits (e.g., incident response, traffic management, and increased security). The scan team found a best practice of lane closure or changing traffic direction (e.g., pneumatically activated lane delineators and zipper barriers that provide for reversible lanes and barriers through tunnels and tunnel approaches). The owners should have an operating procedure that considers safety both for the public and for the owners' personnel.

An incident response manual, separate from the operations manual, should be developed to outline procedures that will require various community, police, fire, and emergency services response in the event of incidents that disrupt traffic and/or increase risks. Periodic drills, including tabletop exercises with appropriate agencies, should be performed.

The scan team findings support restricted transportation of hazardous cargo through tunnels. In the event that no alternate route is available, well-defined emergency response and fire ventilation plans should be in place. Restricting the hours during which hazardous cargo can be transported through tunnels is an option (e.g., from 3 a.m. to 5 a.m. under controlled conditions). The scan also found several preventive operational strategies for hazardous materials; these are covered in Chapter 3.0.

## 6. A tunnel includes a long term commitment to provide funding for preventive maintenance, system upgrades/replacements, and operator training and retention

The decision to build a tunnel is a long term commitment on the part of the owner. Tunnels that include 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. The AASHTO SCOBS should establish a target level of condition, system reliability, and performance for the facility to guide operators and owners on current and future decisions that will require manpower or funding.

As equipment ages, system components will become obsolete and replacement parts will be difficult to find. In particular, electronic equipment, such as computers, SCADA systems, and sensors, becomes obsolete or is no longer supported by its original manufacturer sooner than mechanical equipment does. Periodic upgrades are vital to keep all systems functioning reliably. For these reasons, funding 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.

Owner agencies should develop tunnel preservation guidelines for funding purposes (e.g., for concrete repair and washing of walls).

A separate fund should be dedicated to tunnels, and agencies should work with local funding, planning, and maintenance organizations to accomplish this task. The financial management plan for tunnels should not only include initial costs for construction, but should also address future preservation and upgrading needs. The scan team found that without this dedicated fund, tunnel upgrades do not compete well with system wide needs, such as traffic signals and pavement preservation.

Training, retention, and a succession plan should be developed for tunnel operators. The scan team found best practices that fostered pride of ownership, a “home away from home” culture and “can do anything” attitude..

## 7. Share existing technical knowledge within the industry to design a tunnel

Technical knowledge that exists within the industry should be shared with tunnel owners to provide them with a range of practical tunnel design options. This knowledge base would include domestic and international tunnel scan information, past project designs, construction practices, emergency response best practices, and subject matter experts. Value engineering can improve technology transfer with limited owner experience in tunnel systems (e.g., Value Engineering/Accelerated Construction Technology Transfer).

Design documents, including calculations and as-built documents, should be filed electronically, be easily retrievable by the controlling owner, and be appropriately backed up (e.g., on microfilm).

Recognizing the security concerns of tunnel owners, the scan team believes that actual details and best practices used in tunnels should be shared with prospective and existing tunnel owners without identifying the specific facilities where these details and practices are used.

## 8 Provide education and training in tunnel design and construction.

The scan team findings support training and development for owner agencies. Currently, few civil engineering programs in the U.S. offer a graduate course in tunneling, and it is likely that most civil engineers are not exposed to tunneling. Many DOTs do not have tunnels in their transportation systems; others built their last tunnel 20 to 30 years ago and, therefore, the in-house expertise is either nonexistent or out of date. Information gathered through host presentations, the desk scan, and discussions indicates that the number, magnitude, and complexity of tunneling projects will increase in the next few years. However, the current offering of short courses allows engineers to acquire only tunnel project nomenclature, not the required working knowledge.

Highway tunnel owners and the FHWA should provide their engineers with access to education and training on tunnels that is available through academia and industry. This involvement would also help direct academic research on tunneling. Reputable international online courses and certificates on tunneling would allow engineers to acquire up-to-date information and working knowledge in tunnel design and construction.

# Planned Implementation Actions

The implementation of the scan team’s top eight recommendations will be a step in the process of developing national standards and guidance. Scan findings will also provide data for consideration in the development of a national tunnel inventory. These activities will assist the AASHTO Highway Subcommittee on Bridges and Structures (SCOBS) Technical Committee for Tunnels

(T-20) and the FHWA in developing best practices for roadway tunnel design, construction, maintenance, inspection, and operation for existing and new tunnels.

The scan team anticipates that the lead group for implementation of the scan's recommendations will be the AASHTO SCOBS T-20 in conjunction with the FHWA and the TRB AFF60, working with the National Fire Protection Association (NFPA) and other tunnel organizations. The scan team initially presented its findings and recommendations to the AASHTO SCOBS T-20 during the January 2010 TRB Annual Meeting. Scan team efforts also include distribution of the FHWA Tunnel Safety brochure that was developed following the 2005 international tunnels scan and provision of additional information on the FHWA tunnels Web site. Other activities include coordination and development of research statements related to tunnel needs. To disseminate information from the scan, the team is giving technical presentations at national meetings and conferences sponsored by the FHWA, AASHTO, and other organizations; is hosting webinars; and is planning to write papers for various publications.

The full implementation plan with detailed implementation strategies can be obtained through the AASHTO SCOBS T-20.

CHAPTER 1

# Introduction

## Background

Most highway facility components in the United States are governed by design, construction, maintenance, inspection, and operations codes and regulations of the American Association of State Highway and Transportation Officials (AASHTO) and the U.S. Federal Highway Administration (FHWA). However, to date, highway tunnels in the U.S. do not have comparable national codes and regulations. Recent events, such as the July 2006 suspended ceiling collapse of the I-90 Central Artery/Tunnel (CA/T) in Boston, Massachusetts, have called attention to the need for such national standards.

After investigating the CA/T ceiling collapse, the National Transportation Safety Board (NTSB) recommended that the FHWA seek legislation to establish a mandatory tunnel inspection program that would identify critical inspection elements and specify an appropriate inspection frequency. The FHWA requested Office of the Secretary of Transportation clearance to proceed with regulatory action to develop National Tunnel Inspection Standards similar to the National Bridge Inspection Standards (NBIS)[5] contained in 23 CFR 650, Subpart C.

An Advance Notice of Proposed Rulemaking[6] was published in the Federal Register in November 2008. In July 2010, a Notice of Proposed Rulemaking that addressed comments received on the ANPRM was published in the Federal Register. As of the writing of this report, the FHWA is preparing a Final Rule to address comments received on the NPRM.

## Objectives

The objective of this domestic scan was to assist in addressing the need for national tunnel standards and a national tunnel inventory. The scan's focus was on inventory criteria used by tunnel owners; highway tunnel design and construction standards practiced by state DOTs and other tunnel owners; maintenance and inspection practices; operations, including safety, as related to emergency response capability; and specialized tunnel technologies. The scan also included consideration of fire suppression; traffic management; incident detection and management; and analysis, design, and construction repairs of existing tunnels.

General topics of interest to the scan team were:

- Current criteria owners and states use to identify tunnels in their inventory

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[5] National Bridge Inspection Standards, U.S. Department of Transportation, FHWA, Federal Register, Vol. 69, No. 239, pp. 74419–74439, December 14, 2004, http://www.fhwa.dot.gov/bridge/nbis.htm

[6] National Tunnel Inspection Standards, Advance Notice of Proposed Rulemaking, FHWA, Federal Register, November 18, 2008.

- Standards, guidance, and "best practices" for existing and new roadway tunnels in the US; and
- Specialized technologies currently used for existing and new US roadway tunnel design, construction, maintenance, inspection, and operations.

## Methodology

The team conducted a desk scan to identify agencies that have significant underwater and mountain tunnels in their inventories and use innovative approaches; agencies with ongoing or upcoming tunnel construction projects were also of interest. The scan team developed and sent a list of Amplifying Questions (see Appendix A) to the host agencies prior to the scan.

The scan team investigated tunnels on the state, regional, and local highway systems. While its scope was roadway tunnels, the scan team also visited a transit system.

Abbreviations and acronyms used in this report are listed on page iii. Relevant recent and ongoing research projects are listed in Appendix B.

## Scan Itinerary

The scan itinerary included both meetings with agencies and tours of their tunnels, as detailed in Appendix C.

## Host Agencies

The scan team met with representatives from 13 agencies during two weeks in August and September 2009. Host agencies were distributed geographically across the U.S. Hosts for the first week, along the east coast, were the:

- Chesapeake Bay Bridge and Tunnel District
- Massachusetts DOT (previously the Massachusetts Turnpike Authority)
- Port Authority of New York and New Jersey
- Virginia DOT

Hosts during the second week, in the western U.S., were:

- Caltrans (California DOT)
- Colorado DOT
- Washington State DOT
- City of Seattle (DOT and Fire Department)
- Sound Transit in Seattle

In addition to site visits with scan hosts, the team also held Web conferences with representatives from the Alaska DOT and Public Facilities, the District of Columbia DOT, and the Pennsylvania DOT. The contacts in each of these agencies are listed in Appendix D, and their tunnel inventories are shown in Appendix E.

## Alaska Department of Transportation and Public Facilities (AKDOT&PF)

The AKDOT&PF owns the Anton Anderson Memorial (Whittier) Tunnel[7]. It is 13,300 feet long and is the longest combined highway railroad tunnel in North America. It is located 50 miles southeast of Anchorage and connects the city of Whittier on Prince William Sound to south central Alaska. Converted from a World War II railroad tunnel, it opened as an 11.5-foot-wide, single-lane, bidirectional, multi mode facility in 2000. The tunnel operates on a bi hourly schedule for highway traffic, with intermittent rail traffic. This was the first time in the U.S. that vehicles drove directly over railroad tracks in a tunnel, and the first tunnel in the nation to have jet turbine and portal fan ventilation and computerized regulation of both rail and highway traffic. It was designed for temperatures as low as -40°F and winds of up to 150 mph; its portal buildings were designed to withstand avalanches.

## California Department of Transportation (Caltrans)

Caltrans has 51 existing tunnels, including 24 that are locally or federally owned. It currently has several tunnels under design or construction, including the Caldecott 4th Bore, Devil's Slide, Doyle Drive, 710 Project, and Coronado.

The Posey and Webster Street Tunnels are two immersed tubes on SR 722 connecting the cities of Alameda and Oakland across the Oakland Estuary[8]. The immersed Posey Tunnel carries two-way traffic and was the first precast reinforced concrete immersed tunnel with bituminous coating in the country and the longest in the world when it was constructed in 1928. In 1962, the immersed tube Webster Street Tunnel was built to relieve some of the Posey Tunnel traffic congestion; it is the first and only tunnel designed in-house by Caltrans. A seismic retrofit of the Posey and Webster Street Tunnels was completed in the early 2000s. The retrofit work included jet grout columns at the Posey Tunnel and vibro stone column installation at the Webster Street Tunnel. The current retrofit work includes tube section joint repair, ceiling tile replacement, and additional seismic retrofit work.

The Caldecott and Devil's Slide Tunnels are the first bored tunnels in California since 1973. The Caldecott Tunnel Improvement Project on SR 24, awarded in 2009, is a fourth two-lane bore north of the existing three tunnels to connect Alameda and Contra Costa Counties (see Figure 1.1)[9].

Devil's Slide Tunnel (see Figure 1.2) is located in Caltrans' District 4 on Route 1 between the town of Montara and the Linda Mar District of Pacifica in San Mateo County[10]. The double bore tunnel, with one lane in each direction, is currently under construction through the San Pedro Mountains to bypass the steep and rocky coastline that has had repeated road closures due to the unstable

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[7] North America's Longest Railroad Highway Tunnel: Anton Anderson Memorial Tunnel, Alaska DOT and Public Facilities, May 2009, http://www.dot.state.ak.us/creg/whittiertunnel

[8] U. Dash, T.S. Lee, and R. Anderson, "Jet Grouting Experience at Posey Webster Street Tubes Seismic Retrofit Project," http://www.dfi.org/pubdetail.asp?id=1070

[9] Caldecott Fourth Bore Project, Caltrans, 2009, http://www.dot.ca.gov/dist4/caldecott/

geological formation that results in landslides and rock falls (see Figure 1.2). Scheduled to open in 2012, Devil's Slide Tunnel will be the longest tunnel in the state, at 4,265 feet; currently the longest tunnel in the state is a 4,000-foot federal tunnel in Yosemite.

**Figure 1.1** *Fourth two-lane Caldecott Tunnel bore on SR-24 under construction*

## Colorado Department of Transportation (CDOT)

Colorado has 20 on-system and 10 off-system highway tunnels. Its most significant highway tunnel is the Eisenhower/Johnson Memorial Tunnel (EJMT), which carries I-70 traffic under the Continental Divide (see Figure 21.3). Colorado has five other significant unidirectional tunnels on I-70/US 6, four that are dual-bore and one that is single-bore. Two of those five tunnels are the Hanging Lake Tunnel (HLT) and the Reverse Curve Tunnel (RCT).

The EJMT is a twin-bore tunnel 60 miles west of Denver[11]. The westbound bore opened to two-way traffic in 1973. Once the eastbound bore opened in 1979, each bore then carried one way traffic. At 11,000 feet, the 1.7-mile tunnel is the highest elevation for a vehicular tunnel in the world. The tunnels are approximately 115 feet apart at the east entrance and 120 feet apart at the west entrance. The exhaust ducts and air supply ducts are located above a suspended porcelain enamel panel ceiling. A

**Figure 1.2** *Devil's Slide Tunnel under construction on Route 1 near San Francisco*

[10] Caldecott Fourth Bore Project, Caltrans, 2009, http://www.dot.ca.gov/dist4/caldecott/

[11] Colorado DOT Eisenhower Tunnel, Colorado Department of Transportation, May 2009, http://www.dot.state.co.us/Eisenhower/thetwin.asp

drainage system runs beneath the roadway surface. A walkway adjacent to traffic lanes provides access between the two tunnels through three cross-passages spaced at 2,000 feet; maintenance personnel also use the walkway.


**Figure 1.3** ***Eisenhower/Johnson Memorial Tunnel on I-70 in Colorado***

Opened in 1992, the HLT on I-70 at the midpoint of Glenwood Canyon is 4,000 feet long and consists of two separate two-lane bores with a connecting cut-and-cover section. Each bore carries unidirectional traffic[12]. The tunnel is one of the most technologically advanced tunnel systems in the country. Inside the tunnel is a traffic control and information center that tracks each vehicle traveling through the tunnel via an incident detection and traffic management system of sensors and closed circuit television (CCTV) cameras. A fleet of emergency vehicles is stationed in the middle of the tunnel for 24-hour-a-day response capability, and refuge areas are coordinated with cross-passages. In 2002, a rockslide on the cut-and-cover part of the tunnel cracked the eastbound liner, causing the bore to be closed for repairs when the crack widened in 2007.

The RCT on westbound I-70 at milepost 127 in Glenwood Canyon is a short, two-lane, single-bore tunnel through rock outcropping. The tunnel gets its name from a double curve in the Colorado River at that location.

### District of Columbia Department of Transportation (DDOT)

DDOT has 17 tunnels that range from 107 feet to 3,400 feet in length and are located on I 395 and on city streets. In the fall of 2003, DDOT piloted the first tunnel management system (TMS), which was designed for nationwide use and is available to all highway and transit tunnel owners and operators in the country[13]. In the pilot, DDOT used the TMS to collect and manage data on its 17 highway tunnels. In the fall of 2005, DDOT hosted a workshop that highlighted this implementation. The FHWA and the Federal Transit Administration (FTA) developed and released the TMS in 2003. The system consists of two manuals and a software program. The manuals, *Highway and Rail Transit Tunnel Inspection Manual and Highway and Rail Transit Maintenance and Rehabilitation Manual*, provide guidance on inspection, maintenance, and rehabilitation of highway and rail transit tunnels. The system software is used to collect and manage tunnel component data.

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[12] K.S. Row, E. LaDow, and S. Moler, "Glenwood Canyon 12 Years Later," Public Roads, Federal Highway Administration, Vol. 67, No. 5, March/April 2004

[13] "Showcasing the DC Tunnel Management System," FOCUS, Federal Highway Administration, FHWA-HRT-06-019, October 2005, http://www.fhwa.dot.gov/publications/focus/05oct/02.cfm

## Massachusetts Department of Transportation (MassDOT)

In 1952, the Massachusetts legislature created the Massachusetts Turnpike Authority, which operated on toll revenue and revenue from leases, land and air rights development, and advertisement. The Massachusetts Turnpike Authority owned and operated the 138-mile-long Massachusetts Turnpike (Interstate 90), which extends from West Stockbridge on the New York border to Logan Airport (Route 1A) in East Boston. In November 1, 2009, the Massachusetts Turnpike Authority was consolidated with MassHighways, the Executive Office of Transportation, and the Department of Conservation, creating the Massachusetts Department of Transportation (MassDOT).

In 1997 the state legislature created the Metropolitan Highway System, which includes all seven of MassDOT's tunnels in the Boston area::

- Sumner Tunnel
- Callahan Tunnel
- Prudential Tunnel
- Central Artery North Area (CANA) Tunnel
- Ted Williams Tunnel
- I-90 Connector Tunnel
- O'Neill Tunnel

The three Central Artery/Tunnels (CA/Ts) (Ted Williams, I-90 Connector, and O'Neill) are the newest of MassDOT's seven tunnels. They were built to extend I-90 to Logan Airport and to replace the aboveground Central Artery, restoring surface streets and creating more green space. MassDOT's seven tunnels total approximately seven linear miles, 27 miles of tunnel (including mainline and ramps), and 65 lane miles of tunnel. Air quality has improved in Boston because traffic now flows freely instead of idling for several hours every day, as was the case before the tunnels were completed. MassDOT's District 6 is responsible for the oversight of all tunnel operations, maintenance, inspection, and construction operations.

## Pennsylvania Department of Transportation (PennDOT)

PennDOT and the Pennsylvania Turnpike Commission (PTC) own the highway tunnels in Pennsylvania. PennDOT's oldest tunnels are the Layton and Stowe Tunnels, built over 100 years ago. PennDOT also owns three tunnels built in the 1920s to the 1950s:

- Liberty Tunnel, which carries traffic through Mount Washington to and from the south hills of Pittsburgh and downtown Pittsburgh
- Squirrel Hill Tunnel on I 376, which carries traffic into Pittsburgh from the east
- Fort Pitt Tunnel on I 279, which carries traffic through Mount Washington to and from downtown Pittsburgh

The PTC owns five active tunnels: Allegheny Mountain Tunnel, Blue Mountain Tunnel, Kittatinny Mountain Tunnel, Leigh Tunnel, and Tuscarora Mountain Tunnel. PennDOT is using the FHWA/FTA TMS for collection of condition information on three of its tunnels.

### Port Authority of New York and New Jersey (PANY&NJ)

The PANY&NJ has 28 miles of highway and rail tunnels under its jurisdiction, including two significant underwater vehicular tunnels, the Holland Tunnel and the Lincoln Tunnel, which are supported on clays and silts under the Hudson River.

The two tube Holland Tunnel, known to some as the Eighth Wonder of the World, runs east west under the Hudson River, carrying traffic between Jersey City, New Jersey, and lower Manhattan, New York[14]. When built, it was the first mechanically ventilated underwater vehicular tunnel, and its design and construction methods are still in use today. In 1993, the United States Department of the Interior designated the Holland Tunnel a National Historic Landmark.

The three-tube Lincoln Tunnel runs east west under the Hudson River, carrying traffic between Weehawken, New Jersey, and mid town Manhattan[15]. The outside tubes each carry two lanes of one way traffic; the traffic direction of the two-lane center tube is changed depending on traffic volume, to provide a total of four lanes in one direction. The Lincoln Tunnel was the first to introduce an exclusive bus lane, which is available for commuter travel through the tunnel during weekday morning peak hours.

The PANY&NJ also has a small tunnel, the 41st Street Underpass, in the lowest level of a bus terminal. It extends less than a block and is for bus carriers to use.

### Virginia's Chesapeake Bay Bridge and Tunnel District (CBBT District)

The Chesapeake Bay Bridge and Tunnel (CBBT) District owns and operates the CBBT, which opened in 1964[16]. The CBBT consists of over 12 miles of low level trestle, two one-mile bi-directional tunnels, two bridges, almost 2 miles of causeway, and four manmade islands, totaling 17.6 miles from shore to shore plus 5.5 miles of approach roads as shown in Figure 1.4. It connects Southeastern Virginia and the Delmarva Peninsula (Delaware and the Eastern Shore

Figure 1.4 *Chesapeake Bay Bridge-Tunnel*

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[14] Holland Tunnel, Port Authority of New York & New Jersey Web site, http://www.panynj.gov/bridges-tunnels/lincoln-tunnel.html

[15] Lincoln Tunnel, Port Authority of New York & New Jersey Web site, http://www.panynj.gov/bridges-tunnels/lincoln-tunnel.html

[16] Chesapeake Bay Bridge Tunnel, Chesapeake Bay Bridge and Tunnel District, http://www.cbbt.com/

counties in Maryland and Virginia). The CBBT was selected as one of the Seven Engineering Wonders of the Modern World and employs its own Police Department to patrol the CBBT complex.

The Thimble Shoal Tunnel is 5,734 feet long and the Chesapeake Channel Tunnel is 5,423 feet long. The tunnels pass underneath the 50-foot deep shipping channels at a maximum 4 percent roadway gradient. The tunnel roadway is 24-feet-wide with a 13.5-foot overhead clearance. A 2.5-foot-wide sidewalk on the west side is used in tunnel maintenance and traffic surveillance.

In 1999, construction to expand the original two-lane CBBT to four lanes was completed. The expansion included trestles, bridges, roadways, toll plazas, and maintenance and repair work. The expansion did not include the four manmade islands or the tunnels, which are to be expanded in the future.

### Virginia Department of Transportation (VDOT)

The VDOT has nine highway tunnels. A 2003 flood in the Midtown Tunnel due to Hurricane Isabel led VDOT to revamp its operating procedures at all its tunnels. The I-77 Big Walker and East River Mountain Tunnels freely allow vehicle lane changes inside the tunnel.

The Hampton Roads Bridge-Tunnel (HRBT) is the 3.5-mile-long I 64/US 60 crossing of Hampton Roads Harbor, the body of water that connects the James River to the Chesapeake Bay[17]. The HRBT has two 12 -foot-wide lanes in each direction on separate structures and includes bridges, trestles, manmade islands, and tunnels that connect Norfolk and Hampton in southeastern Virginia. The westbound structure opened to two-way traffic in 1957 and was closed for six months for rehabilitation after the eastbound structure opened in 1976. During the summer approximately 100,000 vehicles cross the HRBT daily. The tunnels are two parallel single tubes built using the immersed sunken tube method. Shipyard built 300 foot long prefabricated tunnel elements were placed by lay barges and then joined together in a trench dredged at the bottom of the harbor and backfilled with earth. state-of-the-art automated traffic control and video monitoring systems are used for traffic management. Ventilation fans circulate fresh air, and air quality is constantly monitored.

The Monitor-Merrimac Memorial Bridge-Tunnel (MMMBT) is the 4.6-mile-long crossing at the mouth of the James River that is a part of the 19–mile-long I 664 freeway, which connects I 64 in Hampton to I-64/I-264 in Chesapeake[18]. Completed in 1992, the MMMBT has two 13-foot-wide lanes in each direction and includes trestles, manmade portal islands, and double-tube tunnels. More than 49,000 vehicles crossed the MMMBT daily in 2004; the 2010 estimate is 60,000 to 70,000. The design speed is 60 mph.

The tunnel is a double-tube that consists of 15 shipyard built 300 foot long prefabricated tunnel elements placed using the immersed sunken tube method and joined in a trench dredged at the bottom

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[17] Hampton Roads Bridge Tunnel, Roads to the Future, December 2007, http://www.roadstothefuture.com/I64_VA_HRBT.html

[18] Monitor-Merrimac Memorial Bridge-Tunnel (I-664), Roads to the Future, September 2004, http://www.roadstothefuture.com/I664_VA_MMMBT.html

of the harbor and backfilled with earth. The tunnel has variable illumination and a computerized information system operated from a central traffic control center. Twenty CCTV cameras with individual television monitors cover the facility and its approaches. There are 34 variable-message signs (VMSs) along the MMMBT.

### Washington State Department of Transportation (WSDOT)

Washington State has 43 highway tunnels with a total length of 27,478 linear feet. A number of short bored tunnels are located on State Highway 14 along the Columbia River.

Built in 1940 and rehabilitated in 1993, the WSDOT's twin-bore Mount Baker Ridge Tunnel (see Figure 1.5)[19] carries I-90 under Seattle's Mount Baker neighborhood to Lake Washington (see Figure 1.5)[20]. Listed on the National Register of Historic Places, the three parallel tunnels carry eight traffic lanes as well as bicyclists and pedestrians. Bored through clay, it is the world's largest diameter soft earth tunnel.

**Figure 1.5** ***Mount Baker Ridge Tunnel on I-90 in Seattle***

The WSDOT and Seattle city and county officials are replacing the central waterfront portion of the SR 99 Alaskan Way Viaduct with a 2-mile-long bored tunnel beneath downtown Seattle[21]. A bored tunnel is expected to be less disruptive to motorists; currently 110,000 vehicles cross the viaduct each day. Construction of the tunnel in this design-build project is scheduled to begin in 2011, and the tunnel is scheduled to be open in 2015.

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[19] Mount Baker Ridge Tunnel, Environment Cultural Resources, Historic Bridges in King County, Washington State DOT, http://www.wsdot.wa.gov/environment/culres/bridges.htm

[20] Mount Baker Ridge Tunnel, Environment Cultural Resources, Historic Bridges in King County, Washington State DOT, http://www.wsdot.wa.gov/environment/culres/bridges.htm

[21] SR 99 – Alaskan Way Viaduct and Seawall Replacement, WSDOT, 2009, http://www.wsdot.wa.gov/projects/Viaduct/

The outside diameter of the tunnel will be approximately 54 feet. It will have two levels that accommodate two 12-foot lanes of unidirectional traffic at each level and will be bored to depths of 100 to 200 feet. The soils are expected to range from soft soils to hard and dense glacier deposited soils. The tunnel will be designed to current seismic standards and include state-of-the-art ventilation, fire-detection and suppression, and lighting systems. The south end of the tunnel will be designed to prevent flooding in the event of a tsunami. The concrete lining will include special gaskets to prevent groundwater seepage. The tunnel will be equipped with a state-of-the-art drainage system with pumps to remove water released by fire sprinklers, runoff from vehicles, and surface water that enters the tunnel.

### City of Seattle (Seattle DOT and Seattle Fire Department)

The Seattle DOT hosted the scan team on a tour of the Battery Street Tunnel on SR 99 in Seattle (see Figure 1.6)[22]. Built in 1952, the tunnel is owned by Washington State and maintained by the Seattle DOT. It is 3,140 feet long and consists of two bores with two lanes in each direction. The tunnel is equipped with ventilation, drainage, and fire suppression systems.

**Figure 1.6A** ***One bore of Battery Street Tunnel***

**Figure 1.6B** ***Battery Street Tunnel control room***

The Seattle Fire Department gave the scan team a presentation on the tunnel's history; risk factors; design fire; tunnel regulations; NFPA standards; and tunnel fire and life-safety systems, which include detection, notification, ventilation exiting the tunnel, and fire suppression.

### Sound Transit

Sound Transit is a public regional transit authority formed in 1995 to provide region wide commuter rail, light rail, and regional express buses to tie together the Seattle region's employment and residential centers and connect the region's cities. Sound Transit hosted the scan team on a tour of its light rail and bus tunnels (shown in Figure 1.7). The tour included a visit to the Beacon Hill Station, which is 165 feet below ground. Sound Transit gave a presentation to the scan tour on geotechnical and other issues related to its transit tunnel construction.

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[22] Battery Street Tunnel, Bridges and Roadway Structures – Other Roadway Structures, Seattle DOT Web site, http://www.cityofseattle.net/transportation/roadwaystructures.htm

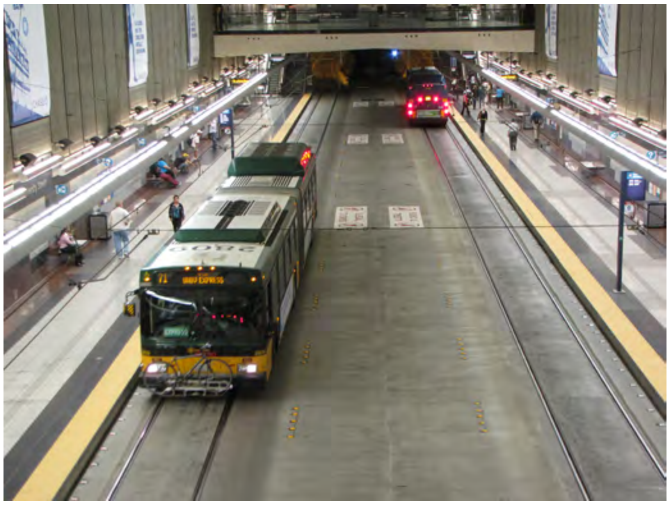

**Figure 1.7A** ***Downtown Seattle transit station***

**Figure 1.7B** ***Sound Transit Tunnel***

## Scan Team

The nine member scan team consisted of two representatives from FHWA, five representatives from state DOTs, an academic member representing the TRB's AFF60, and the report facilitator (see Figure 1.8). Contact information and biographical sketches are given in Appendix F and Appendix G, respectively.

**Figure 1.8** ***Scan team members in Central Artery Tunnel during MassDOT overnight maintenance closure***

Standing, left to right: Louis Ruzzi, Michael Salamon, Jesus Rohena, Mary Lou Ralls, scan coordinator Melissa (Li) Jiang, Barry Brecto, Kevin Thompson, Fulvio Tonon. Kneeling, left to right: Alexander Bardow and Bijan Khaleghi.

CHAPTER 2

# Findings And Observations

This chapter describes the scan team's findings and observations concerning the current U.S. tunnel inventory; criteria the host owners and states use to identify tunnels in their inventories; and standards, guidance, best practices, and specialized technologies the host owner agencies use for their existing and new roadway tunnels, categorized according to design, construction, maintenance, inspection, and operations.

The following details are a compilation of host owner agency responses to the team's amplifying questions, which were posed prior to the scan, and presentations and discussions during the scan.

## 2.1 US Tunnel Inventory

One of the scan's objectives was to assist in addressing the need for a national tunnel inventory. A presentation on the FHWA and FTA TMS (see Section 2.2.6.2page 398 for a description of the TMS) was given during the scan. In its development of the TMS, the investigators identified the following preliminary inventory criteria:

- Basic tunnel information – state, tunnel name, identification number, county, segment or line, route number, year built, height, width, length, vertical and horizontal roadway clearances
- Tunnel construction method – cut-and-cover, shield driven, bored, drill and blast, immersed tube, NATM
- Tunnel shape – circular, rectangular, horseshoe, oval/egg
- Ground conditions – soft, subaqueous, mixed face, rock
- Lining and support system – unlined rock, cast in place concrete, shotcrete/gunite, precast liners, steel/iron plates, masonry, slurry wall/cast in place concrete
- Type of ventilation system – longitudinal, semi-transverse, full transverse, single point extraction, natural
- Location of ventilation jet fans
- Lighting – fluorescent, high pressure sodium (HPS), low-pressure sodium (LPS), metal halide, pipe lighting

### 2.1.1 Number of Tunnels in Inventory

The number of tunnels the scan team hosts own ranges from two to over 40. The number of tunnels specified is dependent on the owner's definition of a tunnel. See Appendix E for a listing of the tunnels.

| Tunnel Owner | No. of Tunnels | Comments |
|---|---|---|
| AKDOT&PF | 3 | |
| Caltrans | 30 | Caltrans currently has 30 tunnels in its state inventory, with three currently in construction. This does not include the tunnels owned by local agencies. |
| Colorado DOT | 30 | 20 on-system and 10 off-system highway tunnels. |
| District DOT | 17 | The tunnels range from 107 ft to 3,400 ft in length and are located on I-395 and city streets. |
| MassDOT | 7 | 47 lane miles of tunnel; 72% of inventory built during the Central Artery/Tunnel project |
| PennDOT | 5 | PennDOT defers to its District 11 concerning how to count the tunnels. |
| Pennsylvania Turnpike Commission[a] | 5 | Currently active. |
| Port Authority of NY&NJ | 3 | |
| VA CBBT | 2 | |
| Virginia DOT | 8 | |
| WSDOT | 43 | Total length of 27,478 ft. |

[a]Pennsylvania Turnpike Commission, as reported by PennDOT.

### 2.1.2 Ages of Tunnels

Ages of tunnels owned by scan team hosts range from 110 years to less than 10 years. Several owners are currently constructing or planning to construct new tunnels.

**AKDOT&PF:** The Whittier Tunnel was constructed over 50 years ago and was rehabilitated over nine years ago.

**Caltrans:** Caltrans tunnel structures are vintage 1920s, 1930s, 1960s, 1990s, and 2000s, and are a history book for the evolution of tunnel design features.

**Colorado DOT:** The Eisenhower bore of the EJMT is 36 years old, and the Johnson bore is 30 years old. The Hanging Lake Tunnel (HLT) and the Reverse Curve Tunnel (RCT) were constructed in the early 1990s and late 1980s, respectively.

**District DOT:** The DDOT tunnels are typically 30 to 40 years old. Major rehabilitation was done in the early 1990s.

**MassDOT:** MassDOT's seven tunnels range in age from eight to 77 years.

**PennDOT:** The Squirrel Hill Tunnel and Fort Pitt Tunnel are over 50 years old. The Liberty Tunnel is over 80 years old. The Stowe TWP-7th St. Tunnel is 100 years old, and the Layton Tunnel is 110 years old.

**PANY&NJ:** The Holland Tunnel opened November 1927. The Lincoln Tunnel Center opened December 1937, the Lincoln Tunnel North opened February 1945, and the Lincoln Tunnel South opened March 1957. The 41st Street Underpass was constructed in 1975.

**VA CBBT:** The CBBT is 45 years old.

**VDOT:** The ages of VDOT tunnels are listed below:

- Westbound Downtown – 57 yrs
- Westbound Hampton Roads Bridge-Tunnel (HRBT) – 53 yrs
- Midtown – 47 yrs
- Big Walker Mountain Tunnel – 37 yrs
- East River Mountain Tunnel – 35 yrs
- Eastbound (EB) HRBT – 33 yrs
- Eastbound Downtown – 23 yrs
- Monitor-Merrimac Memorial Bridge-Tunnel (MMMBT) – 17 yrs

**WSDOT:** The average age of WSDOT tunnels is 49.3 years. The I-90 tunnels are approximately 20 years old.

### 2.1.3 Tunnel Definition

The scan team asked the tunnel owners how they define a tunnel in their agency and whether any consideration is given to length, type of construction, ventilation, or lighting in developing their definition. The team also gave the owners the opportunity to propose changes to the AASHTO tunnel definition.

#### *2.1.3.1 Current Definitions Used by Owners*

The definition of a tunnel varies among owners. The simplest definition is "a structure mined or bored through undisturbed material." Several use the NFPA 502 definition, "An enclosed roadway for motor vehicle traffic with vehicle access that is limited to portals." Others define their tunnels by ventilation and lighting. Some do not have a specific definition.

**Caltrans**: To date, Caltrans Structure Maintenance & Investigations (SM&I) has not had a need to define a tunnel other than for classifying its design-type in the National Bridge Inventory (NBI). SM&I defines a tunnel as a structure mined or bored through undisturbed material. Other Caltrans functional units may have their own tunnel definitions. Refer to the definition in the Caltrans response in Section 2.1.3.2. The definition is based on the tunnel's capability of developing a toxic environment.

**Colorado DOT:** Tunnels are enclosed roadways with vehicle access that is restricted to portals.

**District DOT:** DDOT believes length, type of construction, ventilation, and lighting are all factored into defining a tunnel.

**MassDOT:** MassDOT believes that the definition is not as important, as tunnel inspection is similar to that for bridges. However, the definition matters if specific life-safety systems are associated with the structure. The largest determinant is ventilation. Length is less reliable, as the structure's cross section and the type of vehicles allowed to travel within the structure also affect when ventilation is required. Setting a rigid length guideline can be problematic if conditions of fire risk are not taken into account. Lighting and pump stations are not very informative, as they are often required in underpass situations. MassDOT does not consider roadway bridges over roadways to be tunnels.

**PennDOT:** PennDOT defines its tunnels by lighting and ventilation and follows the AASHTO definition in its tunnels to a certain degree; however, it has no specific tunnel definition in its policies. Three of the four state owned tunnels in the Pittsburgh area have ventilation and electrical systems, including lighting, and were constructed using the traditional excavate/brace as you go method. The fourth tunnel has lighting and no ventilation, but was constructed in a manner similar to that used for the other three tunnels.

**PANY&NJ: The PANY&NJ uses the definitions as provided by NFPA 502 and complies with its ventilation requirements.**

**VA CBBT:** The CBBT District is not an agency and to date has not had the need to define tunnel.

**VDOT:** VDOT uses the NFPA 502 and AASHTO T-20 definitions.

**WSDOT:** WSDOT currently makes no distinction for structure type. If the structure is reported as a tunnel, WSDOT inspects it as a tunnel.

#### *2.1.3.2 Proposed Changes to AASHTO Tunnel Definition*

The tunnel owners were asked if the AASHTO tunnel definition works for them and, if not, what changes they would recommend. The AASHTO tunnel definition is copied below:

> *Tunnels are defined as enclosed roadways with vehicle access that is restricted to portals regardless of type of structure or method of construction. Tunnels do not include highway bridges, railroad bridges or other bridges over a roadway. Tunnels are structures that require special design considerations that may include lighting, ventilation, fire protection*

*systems, and emergency egress capacity based on the owner's determination.*

Some tunnel owners accept the current AASHTO definition without change. Others would like to include a minimum length and life-safety items, including ventilation, fire protection, emergency egress, and lighting.

**Caltrans:** SM&I does not necessarily agree with the last sentence of the definition. To date, SM&I has not had a need to define a tunnel other than for classifying its design-type in the NBI. SM&I defines a tunnel as a structure mined or bored through undisturbed material. The needs of all Caltrans functional units will need to be considered.

The AASHTO definition does not distinguish shorter structures that do not fit within the NFPA 502 definition of a tunnel, but contain the particular conditions of traffic and orientation that result in air quality issues. Caltrans believes that all tunnel type structures have one common issue: the potential for hazardous exposure levels of carbon monoxide (CO) to traffic. Without that criterion, the structure is not a "tunnel." Caltrans offers the following definition that distinguishes a tunnel capable of having a toxic environment from a long enclosed structure. Caltrans uses this as a working definition for classifying structures for inspection as tunnels:

*Tunnels are enclosed roadways with vehicle access that is restricted to portals regardless of type of structure or method of construction. A structure's classification as a tunnel is based on vehicle emission exposure. Roadway structures are tunnels when enclosed enough with access portals, with particular geographical orientation, and with particular traffic geometrics, for computational modeling to show the potential for hazardous vehicle emissions (principally CO, as defined by the EPA) to accumulate to hazardous exposure levels. Tunnels are not dependant on structure length and do not usually include highway bridges, railroad bridges, or other bridges over a roadway. Tunnels are structures that can require special design considerations that may include lighting, ventilation, fire protection systems, and emergency egress capacity, as documented in design standards or based on the owner's determination.*

**MassDOT:** MassDOT believes that some of the European definitions are useful and should be reviewed. The reference to bridges seems unnecessary as owner determination is there. MassDOT recommends the following revision:

*Roadways enclosed on sides and above or enclosed with minimal openings on sides and above with vehicle access that is restricted to a portal or another tunnel regardless of type of structure or method of construction. They are roadway structures that require consideration of systems and procedures to accommodate the enclosed nature of the roadway that may include ventilation, fire protection, emergency egress, and lighting based on the owner's determination.*

**PennDOT:** PennDOT concurs with AASHTO's definition. The PTC has no objection, although depressed roadways are a potential grey area.

**VA CBBT:** The CBBT District believes a minimum length should probably be considered.

**VDOT:** VDOT believes that cargo restrictions based on the design fire size should be incorporated.

**WSDOT:** WSDOT believes that a length component would add value to the definition. As it states, a tunnel may include a series of safety related components that are to be defined by the owner. The majority of these features are in some way related to length.

### 2.1.4 Differentiation between Wide Bridges over Highways and Short Tunnels

Most owners do not differentiate between wide bridges over highways and short tunnels. Instead, differentiation is more typically made by ventilation and lighting.

**AKDOT&PF:** The AKDOT&PF does not differentiate.

**Caltrans:** Caltrans does not differentiate. Bridges are classified by construction type only. Roadway structures are tunnels when enclosed enough with access portals, with particular geographical orientation, and with particular traffic geometrics, for computational modeling to show the potential for hazardous vehicle emissions (principally CO, as defined by the Environmental Protection Agency [EPA]) to accumulate to hazardous exposure levels. Tunnels are not dependent on structure length.

**Colorado DOT:** Tunnels are enclosed roadways with vehicle access that is restricted to portals.

**District DOT:** Structures short enough not to require significant lighting and ventilation are treated as underpasses.

**MassDOT:** When ventilation is required (e.g., due to tunnel length and/or CO concentration), MassDOT treats the structure as a tunnel for structural condition inspection and system testing purposes.

**PennDOT:** PennDOT defines its tunnels by lighting and ventilation. It follows the AASHTO definition in its tunnels to a certain degree but has no specific tunnel definition in its policies.

The PTC excludes a bridge by definition, but then a depressed roadway with cover supporting something other than another roadway becomes a grey area.

**PANY&NJ:** A structure is considered a tunnel if it is longer than 300 feet.

**VA CBBT:** The CBBT District has not had a need to define a difference.

**VDOT:** VDOT uses the NFPA 502 and AASHTO T-20 definitions.

**WSDOT:** Except for a couple anomalies, WSDOT considers structures that carry traffic to be bridges. It has unresolved issues where cut-and-cover tunnels, which are actually lids, carry traffic.

### 2.1.5 Inventory Numbering System

Most owners use a structure numbering system similar to the one they use for their bridges to inventory the tunnels in their states

**AKDOT&PF:** The AKDOT&PF uses a structure number.

**Caltrans:** Caltrans uses a district, route, and post mile and gives all tunnels a bridge number.

**Colorado DOT:** CDOT gives these structure numbers based on a grid system, which is consistent with the numbering of its bridges.

**District DOT:** DDOT uses structure tunnel numbers.

**MassDOT:** MassDOT uses a structure numbering system similar to the one it uses for its bridges.

**PennDOT:** PennDOT uses a Bridge Management System (BMS) number (14 digits). The first two digits are the county in which the structure resides, the next four digits are the state route of the structure, the next four digits are the segment of the state route, and the last four digits are the offset. Tunnels are inventoried as a structure number similar to that used for bridges.

**VDOT:** VDOT bases structure numbers on linear numerical progression.

**WSDOT:** All WSDOT tunnels are numbered in its database, similar to bridges

### 2.1.6 Inventory of Geometric Characteristics Relative to NBIS

Most tunnel owners inventory the geometric characteristics of their tunnels (e.g., clearances, roadway widths, and plenum sizes) similar to the way they inventory geometric characteristics of bridges, in accordance with NBIS criteria.

**AKDOT&PF:** The AKDOT&PF uses as builts and periodic checks by the railroad with a template car.

**Caltrans:** Caltrans follows the NBIS criteria.

**Colorado DOT:** CDOT uses the NBIS criteria for inspecting and characterizing tunnels. For example, structure width is recorded in Item 52, structure length in Item 48, and vertical clearance in Item 10.

**District DOT:** DDOT uses segment numbers and numbers all elements within the segment. It inventories the geometric data differently than the NBIS.

**MassDOT:** The inventory of geometric parameters is done by dividing each tunnel into sections; this is consistent with the bridge inventory. The inventory is similar to the NBIS as it uses the same Structure Inventory and Appraisal sheets for recording. Tunnels have additional data that are input as secondary records coding items.

**PennDOT:** PennDOT inventories geometric characteristics of tunnels similar to bridges (i.e., it inventories clearances and widths similar to the NBIS, using sequential numbering by construction segments).

**VDOT:** VDOT currently uses the design drawings for maintaining this data. It does not keep geometric data in an inventory at this time.

**WSDOT:** WSDOT uses the bridge coding guide as best as possible.

### 2.1.7 Referencing System

Most tunnel owners use a linear referencing system to inventory their tunnels, using mile points, survey stations, construction sections, call boxes, pull stations, detection devices, fire extinguisher stations, access hatches, and doors.

**AKDOT&PF:** AKDOT&PF uses a linear referencing system that is done in feet. Each call box and pull station is numbered, as are detection devices.

**Caltrans:** Caltrans uses survey stations or construction sections. It also uses numbered call box locations and fire extinguisher stations.

**Colorado DOT:** CDOT uses highway mile points as the linear referencing system.

**District DOT:** DDOT uses a linear referencing system with stationing to identify and document the condition of the tunnel elements.

**MassDOT:** MassDOT uses a linear referencing system. It has installed signs and markers in roadways and plenums and is numbering all access hatches and doors to provide control for the inspections. These markers also note the applicable unique inspection tunnel segment based structure or geometry.

**PennDOT:** Tunnels are located in PennDOT's Roadway Management System through a linear reference system.

**VA CBBT:** The CBBT District uses survey stations set at 300 feet.

**VDOT:** VDOT bases its tunnel segments on the design and surveyed baseline stations.

**WSDOT:** WSDOT does not use a linear referencing system for structural inspection purposes.

### 2.1.8 Inventory of Changes in Tunnel Cross Section

Some tunnel owners do not inventory tunnel ramps and other changes in the tunnel cross section as they relate to changes such as in structure type, geometry, and plenum type. Others give them different designations or divide the tunnel into segments based on characteristics, including structure type and geometry.

**Caltrans:** Caltrans has not identified a need to do this for its small tunnel inventory.

**District DOT:** DDOT gives a different designation to delineate them from the main tunnel structure. However, it applies the same inspection and documentation procedures that are used with the main tunnel. A sketch and a word description are provided in the documentation of these other tunnel areas to delineate all ramp structures from the primary tunnel structure. In addition, the TMS provides a pictorial view that indicates the ramp labeling. All ramps are given a specific designation (e.g., Ramp C and Ramp B).

**MassDOT:** MassDOT divides its tunnels into segments (similar to the way it inspects bridges in various segments) that were established based on several characteristics, including structural makeup and geometry. Each segment has constant parameters (e.g., for type, material, and geometry) in the inventoried tunnel. Boat sections are also included in its inventory.

**VDOT:** VDOT considers the entire tunnel facility as a whole during inventory.

**WSDOT:** WSDOT does not differentiate.

### 2.1.9 Inventory of Tunnel Approaches

The tunnel owners vary in how they inventory portals, inclines, and boat sections that lead to the tunnel. Many inventory them as part of the tunnel while others inventory some of them as separate structures.

**AKDOT&PF:** The AKDOT&PF inventories the portals as part of the tunnel but in separate zones. It handles the approaches separately.

**Caltrans:** Caltrans inspects these as part of the tunnel unless they are identified as a separate bridge structure.

**Colorado DOT:** CDOT considers portals and combined portal/bridge abutments parts of the tunnel.

**District DOT:** DDOT inventories portals but not the others.

**MassDOT:** MassDOT inventories its portals and inclines as part of the tunnel. It inventories boat sections as separate structures with their own structure numbers, using the same convention as it uses for bridges.

**VDOT:** VDOT considers the entire tunnel facility as a whole during inventory.

**WSDOT:** WSDOT considers these as part of the tunnel.

## 2.2 Standards, Guidance, and "Best Practices" for Existing and New US Roadway Tunnels

The scan team asked owners about the standards, guidance, and best practices they use for their existing and new tunnels. Their responses are provided below in the categories of design; construction; maintenance, repair, and rehabilitation; inspection; and operations, as well as in a general category.

### 2.2.1 Design

#### *2.2.1.1 Common Design Documents*

The tunnel owners commonly use a variety of design and other standards for their new and existing roadway tunnels, and all use NFPA 502. Many use their own standards in addition to the 2010 AASHTO *Technical Manual for Design and Construction of Road Tunnels – Civil Elements* (see Figure 2.1)[23]. They also use all or part of the FHWA TMS that includes the *Highway and Rail*

*Transit Tunnel Inspection Manual*[24] and the *Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual*[25].

NFPA 502 plays a significant role in establishing design criteria, specific requirements such as for fire and life safety, and references to other resources and standards for tunnels. The full listing of NFPA standards that apply to road tunnels are as follows.

- 10, Standard for Portable Fire Extinguishers
- 13, Standard for the Installation of Sprinkler Systems
- 14, Standard for the Installation of Standpipes and Hose Systems
- 25, Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems
- 70, National Electrical Code®
- 72, National Fire Alarm and Signaling Code
- 101, Life Safety Code®
- 241, Standard for Safeguarding Construction, Alteration, and Demolition Operations
- 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways
- 1620, Standard for Pre-Incident Planning
- 1710, Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments

**AKDOT&PF:** The Whittier Tunnel design was based on a combination of the NFPA 502, FRA, and AASHTO requirements.

**Caltrans:** The following list includes most of the standards used by Caltrans:

- Guidelines for Tunnel Lining Design, ed. T. O'Rourke, American Society of Civil Engineers (ASCE) Technical Committee on Tunnel Lining Design, 1984
- Guidelines for the Design of Tunnels, International Tunnelling and Underground Space Association (ITA) Working Group on General Approaches to the Design of Tunnels, *Tunneling and Underground Space Technology*, Vol. 3, No 3, 1988

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[23] *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*, AASHTO, August 2010

[24] *Highway and Rail Transit Tunnel Inspection Manual,* FHWA, U.S. Department of Transportation, Publication No. FHWA IF 05 002, 2005,

[25] *Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual*, FHWA, U.S. Department of Transportation, Publication No. FHWA-IF-05-017, 2005

- Sprayed Concrete Linings (NATM) for Tunnels in Soft Ground, ed. Institution of Civil Engineers, ICE Design and Practice Guides, 1996
- ACI, Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (ACI 318R-02), American Concrete Institute, Farmington Hills, Michigan, 2002
- LRFD Bridge Design Specifications, 2nd edition – 1998, 2002 Interim American Associations of State Highway and Transportation Officials, Washington, DC, 2002
- Bridge Memo To Designers , California Department of Transportation, Sacramento, California, 1998
- Bridge Design Aids Manual, California Department of Transportation, Sacramento, California, 1995
- Seismic Design Criteria, Version 1.2, California Department of Transportation, Sacramento, California, 2001
- ANSI/AASHTO/AWS D1.5 95, Bridge Welding Code, American Welding Society, Miami, Florida, 1995
- Caltrans Highway Design Manual
- Geotechnical Baseline Reports for Construction – Suggested Guidelines (ASCE)
- American National Standards Institute (ANSI)
- American Society of Mechanical Engineers (ASME)
- American Society for Testing and Materials (ASTM)
- Building Officials and Code Administrators (BOCA)
- Institute of Electrical and Electronics Engineers (IEEE)
- Insulated Cable Engineers Association (ICEA)
- International Conference of Building Officials (IBCO)
- National Fire Protection Association (NFPA)
- National Electrical Code (NEC)
- National Electrical Manufacturers Association (NEMA)
- National Electrical Safety Code (NESC)
- Occupational Safety and Health Administration (OSHA)
- Underwriters Laboratories
- Uniform Building Code (UBC)

- Uniform Fire Code (UFC), State of California, Dept. of Transportation, Standard Specifications
- California Fire Code
- CFC California Electrical Code
- Caltrans State of California, Department of Transportation, Standard Specifications
- State of California, Dept. of Transportation, Standard Special Provisions

Caltrans has a documented design standard for fire protection and ventilation features.

**Colorado DOT:** CDOT uses NFPA 502 and has just started using the new AASHTO *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*.

**District DOT:** DDOT uses the FHWA TMS, with its two manuals. It also uses NFPA 502 and Illuminating Engineering Society of North America (IESNA) RP 22, Tunnel Lighting.

**MassDOT:** In addition to NFPA 502 and AASHTO, specific design criteria based on existing tunnels in the U.S. and abroad were prepared for the CA/T project. CA/T Project Design Criteria, Volume II, Section V – Structural, Chapters 10 (Cut-And-Cover Structures), 11 (Immersed Tubes), and 16 (Boat Structures), which were developed by the project, were used for design of the CA/T tunnel and boat structures.

**PennDOT:** PennDOT has used NFPA 502; PennDOT Design Manual 4, Tunnel Engineering; and ANSI and IES guidelines.

**PANY&NJ:** The PANY&NJ uses IESNA RP 22. From a mechanical perspective, the PANY&NJ complies with NFPA 502 for new tunnels. For its existing tunnels, it complies with some, but not all, of the requirements of NFPA 502; it is grandfathered on some requirements because of tunnel age.

**VA CBBT:** The CBBT District's tunnels are 45 years old; any new maintenance projects use the current NEC, AASHTO, and NFPA 502, as well as any other required industry standards.

**VDOT:** : VDOT uses the NFPA 502 and FHWA related manuals.

**WSDOT:** WSDOT uses industry standards, including NFPA 502 and referenced NFPA and other standards; WSDOT design manuals, standards, and practices; ANSI/IESNA RP 22; *Manual on Uniform Traffic Control Devices*; and applicable International Building Code, AASHTO, and Institute of Transportation Engineers standards and guidelines.

### 2.2.1.2 Rationale for Choosing Parameters for Tunnel Projects

The tunnel owners' rationale for choosing certain parameters for their tunnel projects (e.g., reasons for choosing one alignment over another or for choosing a certain construction method over another) included many factors. Lower cost and lower risk are primary considerations. Other considerations include tunnel length, geometric and other site constraints, geological conditions, environmental impacts, traffic requirements, and maintenance considerations.

**AKDOT&PF:** Converting the existing railroad tunnel instead of a separate new tunnel was determined to be less risky and more economical to build. The short tunnel provided a visual screen.

**Caltrans:** For structures, Caltrans looks at the geologic profile, design variations, environmental impacts, maintenance operations, costs, and traffic demand. It spends considerable time and resources in developing tunnel locations, alignments, and type of construction. Some of the issues it typically includes in deciding on the most appropriate location and type of tunnel are traffic flow and demand, environmental impacts, geological conditions, type of construction and overall cost of tunnel alignments. The length and geological condition dictate the most appropriate type of tunnel construction. Its two recently designed tunnels are using SEM due to the short lengths and the geology. The 710 project, which is estimated to be in the range of three to five miles, may be more cost effective if a TBM is used.

Many of the M&E features employed are based on local maintenance capabilities and their requirements to conform to their highway design-type manuals. These include SCADA and traffic control features, security, traffic management and communication features, and lighting. Most of the M&E features for fire and life-safety are based on conformance to electrical codes, Cal-OSHA, NFPA codes, and Homeland Security-related requirements.

Operations and monitoring of tunnel facilities are becoming increasingly complex and design intensive. Caltrans has a documented design standard for fire protection and ventilation features that includes a discussion of remote monitoring facilities: "Nearly every proposed tunnel project to date has initially assumed remotely operated tunnel operations. Maintenance and operation centers dedicated to the tunnel structure are normally not initially budgeted into a project, are assumed not to be needed, and adequate access for such a facility is neither available nor allowed for. Monitoring the tunnel operations for traffic incident response and fire/life-safety incident response is a real and often underappreciated design consideration. Maintenance and operation agreements between local agencies and the DOT are required as well as agreements for the local Traffic Management Center (TMC) to receive and monitor tunnel telemetry. These agreements go hand in hand with the Emergency Response Plan documented and required by the latest edition of NFPA 502. For tunnels that include ventilation equipment, agreements and provisions for remotely operated tunnel operations are required as part of the preliminary design proposals. If these agreements cannot be secured, then provisions for maintenance and operation centers will be required."

Hazardous cargo restrictions and access to tunnel facilities are often limited to the fire/life-safety capabilities of the tunnel features. Caltrans has a documented design standard for fire protection and ventilation features that includes a discussion of hazardous cargo accommodation:

> *The selection of the design fire size shall consider the types of vehicles that are expected to use the tunnel, and the design fire size shall be used to design the emergency ventilation system. Structural limitations that potentially limit the capabilities of required ventilation*

*will not be allowed. Legal transportation restrictions (Vehicle Code Ordinances) on the tunnel usage are required to address reduced ventilation capabilities. Essentially, if vehicles that constitute a fire hazard are allowed into a tunnel, but the structure size will not accommodate ventilation equipment in accordance with the latest edition of NFPA 502 to meet that hazard, then those vehicles must be restricted rather than an engineering exemption to limit the size of the ventilation equipment.*

**Colorado DOT:** The EJMT alignment was selected to avoid a major mountain pass (Loveland). The HLT alignment was chosen to resolve critical highway curvature issues and protect the environment.

**MassDOT:** Geotechnical conditions, cost, schedule, the environment, and impact on abutters were all factors. MassDOT has used many different parameters for many differing reasons. Slurry walls were used through the downtown section where the alignment did not have any additional width for temporary support walls. In locations where the width allowed, traditional temporary walls were constructed, allowing backside waterproofing of the permanent structure. Immersed tubes were used to prevent blocking waterways, and precast jacked tunnels were used under active railroad lines.

**PennDOT:** PennDOT considers lowest first cost, right of way, and ease of maintenance.

**VA CBBT:** The CBBT District's rationale involves three key parameters: safety, proven reliability (e.g., design and product), and cost. Alignment for its facility was done through many factors, which included borings, channel location, and water depths.

**VDOT:** VDOT uses the previous success/failure of each parameter, as well as political influence.

**WSDOT:** WSDOT looks at technical feasibility, design parameters, cost, and risk (e.g., geotechnical, right of way, and contamination). Maintenance of traffic during construction is a major factor that WSDOT considers during the selection of the preferred alternative and the alignment of that alternative. Most of the alignment decisions are based on maintenance of traffic considerations.

#### 2.2.1.3 Clearance Envelope Requirements for Design

Tunnel owners determine clearance envelopes for design based on cost, risk, technical feasibility, geometric limits, vehicle configurations, life-safety requirements, and federal and state requirements.

**AKDOT&PF:** The Whittier Tunnel clearance envelope was the railroad clearance requirements for double stack cars.

**Caltrans:** Vertical clearances are mandated in the *Caltrans Highway Design Manual* based upon agreements with the FHWA and Department of Defense. The minimum vertical clearances for major structures are as follows:

- 16-feet 6-inches for freeways and expressways except overlay projects
- 16-feet 0-inches for overlay projects
- 15 feet for conventional highways, parkways, and local facilities
- Above +2 feet for pedestrian overcrossing

The structure envelope required to accommodate the ventilation fan equipment and mounting structure is often the driving criterion for structure size.

**Colorado DOT:** The EJMT was restricted to 13 feet 6-inches until recently. Current allowable clearance is 13 feet 11 inches. The HLT used the required clearances for Interstate highways.

**District DOT:** 14 feet 6 inches is optimal.

**MassDOT:** MassDOT posts a 13-foot 9-inch minimum vertical clearance based on a 14-foot tunnel clearance envelope. However, two older tunnels have lower clearances and are posted at 13-feet 4-inches and 12-feet 6-inches.

**PennDOT:** PennDOT lowered the roadway 4-inches on the Ft. Pitt Tunnel, thus increasing the clearance to 14-feet 3-inches. This reduced the tunnel hits from one a month to only one since 2003. The PTC designs to 16-feet 6-inches of vertical clearance with 12-foot lanes and safety walks in accordance with federal and state standards, and lowered the original surface in the 1960s where applicable.

**VA CBBT:** The CBBT District's original design of 45-year-old tunnels used the current industry standards of the day.

**VDOT:** VDOT uses other area tunnels and Interstate clearances around the proposed tunnel.

**WSDOT:** The Alaska Way Viaduct (AWV) Tunnel size was selected based on limits to technical feasibility (i.e., the tunnel is the largest in the world), cost, risk, and design geometric limits. Since oversize loads are prohibited from the current route and will not be allowed in the future, a 15-foot vertical clearance was selected. In order to accommodate trucks, 12-foot lanes were selected. A 6-foot shoulder is placed on the exit door side of the tunnel in order to allow motorists to safely pass from a disabled vehicle to the exit doors. This means that the larger shoulder is on the driver's left on the southbound lanes. The maximum shoulder width that could be achieved with a stacked bored tunnel was selected: one 2-foot shoulder and one 6-foot shoulder.

#### 2.2.1.4 Seismic Design Criteria

Seismic design criteria vary among tunnel owners. Some tunnels are not designed for seismic loads because they are not located in seismic regions. Others have site specific seismic design criteria.

**Caltrans:** Caltrans' tunnels are typically designed for "no collapse," meaning that they can sustain significant damage and might not be opened to traffic for an extended amount of time. If a tunnel is designated as a lifeline facility, the tunnel and its related structures (e.g., portals, retaining walls, and support buildings) are designed for minimal damage at the safety earthquake evaluation level, meaning that the facility would be functional for emergency traffic within 72 hours of the seismic event.

- Safety Earthquake Evaluation (SEE) = 500- to 1500-year return period
- Functional Earthquake Evaluation (FEE) =100- to 300-year return period
- Construction Earthquake Evaluation (CEE) = 100-year return period (CEE is used for staged construction of retaining walls due to the long timeframe of construction.)

Examples:

- Caldecott (Important Facility)
  - SEE = 1500 years
  - FEE = 300 years
  - CEE = 100 years
- Doyle Drive Tunnels
  - SEE = 1000 years
  - FEE = 108 years (recovery route)

**MassDOT:** MassDOT developed its seismic design criteria for the CA/T Project. Site specific seismic design criteria were developed for structures as listed in Section 2.2.1.1 in accordance with the following:

- "General Criteria for Seismic Design of Underground Structures"
- "Special Criteria for Seismic Design"
- "Seismic Assessment – I-90 Immersed Tube Tunnel"

These documents are part of the CA/T Project Design Criteria, Section V, Appendix B – I, II, and III, respectively.

**PANY&NJ:** *The Project Design Criteria Manual* for "The Tunnel" project adopts a two level earthquake hazard design approach. The two levels are the Operating Design Earthquake and the Maximum Design Earthquake (MDE), defined as follows:

- The Operating Design Earthquake (ODE) is defined as an earthquake event that has a return period of 500 years. When subjected to the ODE, structures should be designed to respond essentially in an elastic manner. There should be no collapse and no damage to primary structural elements. Only minimal damage to secondary structural elements should be permitted, and such damage should be minor and easily repairable. The structure should remain fully operational immediately after the earthquake, allowing a few hours for inspection.

- The MDE is defined as an earthquake event that has a return period of 2500 years. Following the MDE, some interruption in rail service should be permitted to allow for inspection and repairs. When project structures are subjected to the MDE, it is acceptable that they will behave in an inelastic manner. There should be no collapse with danger to life, and any structural damage should be controlled and limited to elements that are easily accessible and can be readily repaired. Structures should be designed with adequate strength and ductility to survive loads and deformations imposed on them during the MDE, thereby preventing collapse and maintaining life safety.

**VA CBBT:** Seismic design was not considered when the CBBT tunnels were designed about 50 years ago. Even today, considering that the CBBT facility is located in a region of low seismic risk, seismic design criteria may not govern the tunnel design in any significant manner. When the parallel crossing bridges and tunnels were designed in the early 1990s, seismic criteria did not govern. For recent and current practice, the CBBT District has used the following papers as guidance on seismic design criteria of tunnels:

- "A Seismic Design of Underground Structures," C. M. St. John and T. F. Zahrah, *Tunneling and Underground Space Technology*, Vol. 2, No. 2, pp. 165 167, 1987
- "Seismic design and analysis of underground structure," Youssef M. A. Hashash, Jeffrey J. Hook, Birger Schmidt, and John I Chiang Yao, *Tunneling and Underground Space Technology*, Vol. 16, No. 4, pp. 247 293, 2001

**VDOT:** VDOT uses the Uniform Statewide Building Code when dealing with seismic design; however, it is not required for the Tidewater area, nor was it required for the mountain tunnels at the time of their design and construction.

**WA Sound Transit:** Sound Transit followed guidelines in the *Sound Transit Design Criteria Manual* for design, which requires analysis for both an MDE (2500-year event) and an ODE (150-year event).

**WSDOT:** For the bored AWV Tunnel, WSDOT used a dual level 2500 year and 100-year recurrence interval. For the cut-and-cover tunnel, a 1000-year recurrence interval is used. Portal structures are included with cut-and-cover tunnel and U section structures. The tunnel lining and interior roadway structure are included with the bored tunnel.

#### *2.2.1.5 Correlation of Seismic Strains to Liner Collapse Mechanism and to Acceptable Damage and Leakage Rates*

Correlation of seismic strains to tunnel liner collapse is handled on a site specific basis. For example, strain limits due to seismic loading for a recent tunnel project in Washington were 0.004 for concrete and 0.006 for steel reinforcing bar for a 2500-year event. Site specific seismic design criteria vary with respect to different return periods, acceptable strain limits in steel and concrete, and the owner's willingness to balance risk and cost. Given the design meets the site specific strain limits, the tunnel owners believe that the development of a liner collapse mechanism is unlikely, although some significant deformation, cracking, and spalling could occur. Similarly, they would not expect leakage. No known correlation is readily available for strain limits versus apparent damage and leakage.

**Caltrans:** In its seismic design criteria, Caltrans designs for minimum ultimate or service strain capacity of 0.06 to 0.09 for steel, 0.005 for concrete with low confinement, and 0.015 for concrete with high confinement. These limits are above the limits of 0.006 for steel and 0.004 for concrete. Therefore, Caltrans does not anticipate seeing any damage to structures with strain limits of 0.006 for steel and 0.004 for concrete.

A 100-year seismic event in California would most likely be less than Caltrans' FEE. Caltrans would typically design the structure and elements to remain elastic and would not expect any damage or very limited (i.e., easily repairable) damage. It would not expect any leaking at a 100-year event.

**VDOT:** The Bristol District tunnels were constructed using WVA 1960 Code as amended in 1965; no seismic design.

**WA Sound Transit:** Sound Transit considers collapse of the liner to be highly unlikely given the interaction of the liner with the surrounding ground. Even in the case of local compressive failures of the lining at very high compressive strains (exceeding about 0.003 strain in the concrete) or local significant yielding and deformation of reinforcement in tension (well in excess of the 0.006 strain in the steel), the development of a collapse mechanism is considered unlikely. The U-Link design used a concrete compressive strain limit of 0.002, at which point concrete still maintains its full compressive strength, and a steel tensile strain limit of 0.006, at which point the steel is yielding, but also still maintaining its full strength. Some significant deformations, cracking, and spalling are likely to occur at these strain levels, but the lining system will maintain its integrity without collapse.

The goal for strains within these limits is to maintain the elastic behavior of the lining, which should limit cracking and subsequent leakage to a minimum for the ODE event. No known correlation is readily available for strain limits versus apparent damage and leakage, but past performance of segmental linings during earthquake events is very favorable. The U-Link design did have ODE strains just slightly in excess of these limits; however, this was due to the high static loads, not so much the additional ODE seismic loads. All static plus ODE loads fell well within the moment thrust interaction diagram capacity envelope (LRFD strength design).

**WSDOT:** WSDOT's design criteria strain parameters lack experimental evidence of performance characteristics. The engineering analysis concludes that conservatism exists in the values and stands as the basis of designs.

#### *2.2.1.6 Seismic and Other Criteria for Portals and Approach Structures*

Some owners use the same seismic and other criteria for portals and approach structures as the main body, while others use higher or different criteria for their portals and approach structures.

**Caltrans:** For the Devil's Slide Tunnels, the criteria for the portals are higher than for the main body of the tunnels. For the Caldecott Tunnel, the seismic criteria for the portals and approach structure were the same as for the main body.

**Colorado DOT:** The HLT external portals included rock-fall protection "designed in" based on specific geotechnical recommendations.

**MassDOT:** The CA/T Project used the same methodology for approach/transition structures as it did for the main body seismic criteria.

**VDOT:** The Bristol District tunnels were constructed using WVA 1960 Code as amended in 1965; no seismic design.

**WA Sound Transit:** Analysis procedures and design criteria for underground portals and approach structures are similar to those used for tunnels but focus more on racking analysis and meeting deformation and ductility requirements for the structures based upon frame analysis. Its design criteria give requirements for concrete box structures, which are usually used at portals and approach structures (cut-and-cover tunnels).

**WSDOT:** For the AWV Tunnel, the cut-and-cover tunnels, boat sections, and portal approach walls are designed to resist a 1000-year recurrence interval consistent with the AASHTO *Guide Specifications for LRFD Seismic Bridge Design*, 1st edition.

#### 2.2.1.7 Tunnel Life Expectancy

The tunnel structure life expectancy varies from 50 to 125 years and longer with adequate maintenance. The various tunnel components have different life expectancies, with M&E systems typically having a 10  to 25 year life and fire suppression systems having a 50 year normal life expectancy. Functional obsolescence due to changing traffic needs or structural deficiency due to changing design criteria is likely to occur prior to the end of tunnel life.

**AKDOT&PF:** The design for some tunnel equipment is 20 years, with a recovery account being maintained to replace items that fail.

**Caltrans:** Devil's Slide: 100 years; Caldecott: 100 years; Doyle Drive: 75 years

**District DOT:** DDOT has not performed a life expectancy analysis on its tunnel inspection contracts, but would expect a minimum of 100 years if the tunnel is properly maintained.

**MassDOT:** Various components have different life expectancies. The CA/T tunnels structures were designed for AASHTO's 75-year service life-cycle. Older tunnels that MassDOT operates indicate major rehabilitation is necessary after approximately 50 years. M&E systems require replacement more frequently, in the range of 10 to 25 years.

**PennDOT:** PennDOT's tunnels range in age from 29 years to 85 years. Three tunnels will have been rehabilitated by 2014. At 85 years, Liberty is expected to last until it is at least 125 years old.

**VA CBBT:** In the 1950s and 1960s, the timeframe for which the CBBT tunnels were designed, it was generally standard practice for codes and standards to be based upon a life expectancy of 50 years. Thus, although the CBBT District is not aware of an explicitly stated life expectancy for its tunnels, following the standards, codes, and guidelines in practice at that time would result in a 50 year life expectance. With diligent maintenance practices, such as those that are in place at the CBBT, life expectance can be significantly extended. However, even with diligent maintenance, a facility such as the CBBT tunnels can be faced with functional obsolescence or structural deficiency. Functional obsolescence can be the result of changing geometric requirements, such as horizontal or vertical clearances or increases in traffic resulting in a deficient service level. Structural deficiency can result from changing design criteria, such as increasing the minimum design load requirements.

**VDOT:** VDOT used AASHTO's 75-year service life-cycle.

**WA Sound Transit:** A 100-year design life is required for these structures. Key components of the lining (e.g., concrete cover requirements, sealing gaskets, and inserts) are designed for the 100-year design life.

**WSDOT:** For the AWV Tunnel, a 100-year service life is substantiated by engineering analysis.

#### *2.2.1.8 Poor Soils*

Tunnels owners have used various methods to mitigate poor soil conditions, or they have designed the tunnels to function in the poor soils. Soil improvement methods have included jet grout columns, stone columns, deep-soil mixing, soil freezing, compacted granular fill replacement, and hydrodensification.

**Caltrans:** Caltrans will generally try to improve the poor soils or design the structures to function in the poor soils. For the Posey/Webster Tunnels, Caltrans mitigated the liquefiable soils by installing jet grout columns and stone columns. For the Doyle Drive Southbound Battery Tunnel, Caltrans will mitigate the liquefiable soils by a ground improvement scope of work: cement deep-soil mixing at the tunnel location.

**MassDOT:** MassDOT has done soil freezing and deep-soil mixing as described below:

- MassDOT used soil freezing to jack a tunnel under rail tracks. The tunnel was a concrete box 8 feet below the tracks and could not affect track geometry. The jacking pit was constructed, freeze pipes placed, the ground frozen over three to four months, the tunnel segments built, and the frozen soil excavated as the tunnel box was pushed forward 1 foot each day. Frozen clay consolidates as it thaws, and the project is now seeing settlements of 6-feet where the soil was frozen to a depth of 80 to 90 feet. This has required the rails to be re ballasted to maintain track geometry.
- MassDOT used deep-soil mixing of unconsolidated clays, injecting grout to a depth of 80 to 90 feet with a deep-soil mix rig that had 5-foot diameter mixing paddles.

**PennDOT:** The PTC used NATM classifications and support parameters applied to various conditions as classified during excavation.

**PANY&NJ:** Treatment is required if proposed structures are located in areas where support will be provided by soils that may liquefy in a postulated seismic event. A number of options may be explored in order to obtain the most cost-effective solution. A few examples are cited for explanation purposes:

- Excavation and replacement with compacted granular fill,
- Mix-in-place treatment using large diameter augers to mix in situ soil and cement grout in order to achieve a ground mix strength of 100 to 150psi,
- Jet grout columns,
- Stone columns, and
- Hydrodensification.

**VA CBBT:** In the original construction, the CBBT District used surcharge area and/or changed alignment.

**VDOT:** VDOT removes unsuitable materials and replaces them with competent fill.

**WSDOT:** WSDOT evaluates response and mitigates if necessary with deep foundation support, in ground ductility, or soil remediation.

#### *2.2.1.9 Maintenance Considerations in Design*

Tunnel owners include facility maintenance and management staff early in the design process and through task force meetings, manuals, and plan reviews to ensure maintenance requirements are considered in design. These considerations include locating M&E systems and signage to avoid interference with tunnel washing operations, placing drain cleanouts at appropriate distances, and placing lighting at higher elevations to avoid vehicular hits. Suggestions for how maintenance could be better considered in the design phase of new tunnels include:

- Avoiding traffic disruption (e.g., lane closures) when accessing various rooms and when maintaining or repairing various components, such as signs and lighting
- Building in redundancy in control system communications and processors
- Designing attachments for safety and maintainability in addition to aesthetics
- Using black ceilings, which minimize cleaning, in conjunction with modern lighting technology to provide adequate roadway illumination
- Containing the hydrant main within the tunnel
- Using alternate solutions such as precast concrete wall panels with ceramic tiles or vitreous enamel-coated fiber cement panels for walls and ceilings

**AKDOT&PF:** The Whittier Tunnel design is easy to maintain because it:

- Has no catwalks, substantial railings, or joints of concern

Uses a bucket truck for light maintenance

- Has exposed conduit, which does run the risk of damage, but is easily repaired
- Has loop detectors that have been trouble-free
- Has drains that have cleanouts at appropriate distances

The tunnel's VMSs are older, but AKDOT&PF's only maintenance concerns have been with power supplies, which are frequently damaged, resulting in the loss of line power.

**Caltrans:** Access and lighting throughout the facility is good. During washing, many obstacles (e.g., signage, lighting, call boxes, and sensors) make it necessary to miss spots. When washing some tunnels in California, the soap and water must be reclaimed for proper disposal.

Many of the M&E features are based on local maintenance capabilities and their requirements, in conformance with their highway design-type manuals. These include SCADA and traffic control features; and security, traffic management and communication features; and lighting. Most of the M&E features for fire and life-safety are based on conformance to electrical codes, Cal-OSHA, NFPA codes, and Homeland Security-related requirements.

**Colorado DOT:** The HLT included maintenance staff on the design/construction team; they later became tunnel operations staff.

**District DOT:** DDOT believes more attention could have been directed to maintainability when its tunnels were designed. It recommends that the following requirements be considered for all new tunnels:

- Electrical rooms and plant and equipment rooms should be accessible by maintenance personnel without the need to stop in or close a travel lane (e.g., a breakdown bay).
- VMS gantries should always include a catwalk/gantry to enable maintenance/repair without stopping in or blocking a travel lane. Signs should always be accessible from the rear, not the front.
- Redundancy should always be required in control system communications and processors.
- Ceiling panels should never be used. If they are used, safety and maintainability rather than aesthetics should dictate the design of attachments.
- New tunnels should not have white ceilings. With modern lighting technology, adequate roadway illumination can be achieved with black ceilings. Cleaning white tunnel ceilings is very difficult and expensive.
- The tunnel hydrant main should always be contained within the tunnel and not run outside the tunnel envelope. This makes it easier to maintain and easier to control operation of isolating valves.
- Tunnels should not be lined with ceramic tiles. Alternative solutions (e.g., vitreous enamel-coated fiber cement panels) are easier to maintain.

**MassDOT:** Older tunnels have steel panels with a baked enamel finish; tunnels that are more recent have precast concrete wall panels with ceramic tiles. The baked enamel surfaces are easier to clean than the tiles but less resistant to accident damage.

**PennDOT:** PennDOT has placed lights at higher elevations to reduce vehicle hits. It uses cable trays for cell phone conduits to make neat runs (i.e., the conduits are not haphazardly placed). PennDOT uses tiles for some walls and ceilings for ease of cleaning.

**PANY&NJ:** The PANY&NJ facility management staff is engaged early in the process (e.g., to value engineer the maintenance and operations practices and procedures and assess impacts to cost and customer service).

**VA CBBT:** Lights are designed to withstand 150 psi pressure washing, surfaces are designed for easy cleaning, roadways are designed with wearing surface to protect concrete, and steel catwalk railings have powder coating.

**VDOT:** During design, maintenance personnel provide input on all aspects of the tunnel.

**WSDOT:** WSDOT incorporates maintenance considerations in various ways (e.g., through task force meetings, manuals, and plan reviews).

### 2.2.2 Construction

The only road tunnel in construction during the scan team visits was the Caltrans Devil's Slide Tunnel.

#### *2.2.2.1 Recent Best Practice Construction Methods*

The tunnel owners consider best practice construction methods to include the following:

- Partnering with the contractor in decision making
- Contingency planning to maintain traffic flow
- Installing jet grout columns and stone columns in liquefiable soils to act as barrier walls
- Using rock reinforcement and shotcrete as permanent stabilization
- Using sequenced excavation
- Using cofferdams and other in water methods during the construction of immersed tubes
- Supporting tunnels on caissons
- Using better-performing materials, such as stainless steel, and more efficient lighting

**Caltrans:** In order to improve tunnel stability, Caltrans dewatered the ground ahead of excavation at the Devil's Slide Tunnels by installing long sub-horizontal drains from the opposite portal. Jet grout columns and stone columns were installed as part of the seismic retrofit of the Posey/Webster Tubes along the outside walls. The jet grout columns were used to strengthen the tube support platforms. The jet grout columns and stone columns were installed in liquefiable material and act as a barrier wall to prevent the liquefied material from flowing underneath the tubes and causing them to lift up.

**Colorado DOT:** For the HLT, CDOT used an innovative technology utilizing sequenced excavation, the use of rock reinforcement and shotcrete as permanent stabilization, and partnership decision-making between the contractor and engineer for excavation support. This saved construction dollars and allowed an accelerated construction schedule.

**MassDOT:** MassDOT has recently used a number of construction best practices on its CA/T Project, as listed below:

- MassDOT cast immersed concrete tubes to be used under Fort Point Channel in a casting basin on the South Boston side. After casting each set of tubes, the cofferdam enclosing the basin was breached and the tubes floated out in three sections.
- For the Ted Williams Tunnel, steel immersed tubes were fabricated in Sparrows Point in Baltimore County, Maryland, and then were floated to Boston, where they were fitted out (cast concrete shell). The tubes were then lowered into place; towers attached to the tubes allowed them to be placed. Railroad couplers joined the tubes, and the water was drained from the 3-foot vestibules (6-feet total for the two tubes). The resulting vacuum pulled the two tubes tightly together, and divers then checked the seal (rubber gaskets were used as seals).
- Tubes were set over the Red Line tunnel (unreinforced construction built in the early 20th Century). The tubes were set on caissons that were drilled on either side of the Red Line. This operation had only one half inch design tolerance, and actually hit within one quarter inch.
- Part of the CA/T Project used soldier pile tremie concrete slurry walls to form the permanent outer walls of the tunnels. The piles are 3-foot beams, 5 foot on center in a 42-inch trench. Steel wide flange soldier piles at 5-foot average spacing were installed in a 42-inch slurry trench; the tremie concrete was then cast to form the wall.

**PennDOT:** For the North Shore Connector project, the Port Authority of Allegheny County used jet grouting, replacing a pile supported highway bridge foundation with a caisson/post tensioned slab foundation, O cell testing of the caissons, and special contingency planning for traffic if the load transfer of the highway bridge failed.

**VA CBBT:** In its tunnels, the CBBT District has performed concrete restoration, fixed delaminated tile and concrete, removed steel and replaced it with 316 stainless steel, and replaced the original lighting with T-5 and T-8 lamps.

**VDOT:** VDOT uses the sunken (i.e., immersed) tube method to deliver precast sections because of the abundant waterways in the Tidewater area.

#### *2.2.2.2 Tunnel-Boring Machine Manufacturer Support and Maintenance*

Although shields were used to excavate road tunnels (e.g., New York City), to date no road only tunnel in the U.S. has been constructed by means of a tunnel TBM. The Downtown Seattle Transit

Tunnel, which was built as both a road and rail tunnel, was constructed using an open breast TBM and opened for buses in 1990. Upcoming examples will be the Port of Miami Tunnel in Florida and the SR 99 Alaskan Way Viaduct Tunnel in Washington.

**Caltrans:** Caltrans may use TBMs for the first time on its I 710 project in Southern California.

**MassDOT:** MassDOT has not used TBMs.

**PennDOT:** PennDOT has not used a TBM for construction of any of its highway tunnels. However, a TBM was used to construct a transit tunnel under the Allegheny River as part of the Port Authority of Allegheny County's North Shore Connector project in Pittsburgh. The maintenance and support were the responsibility of the contractor. The manufacturer was actively on site during the project, especially during assembly, start up, and removal. There were major mechanical issues with the TBM throughout the life of the project.

**PANY&NJ:** The PANY&NJ obtained extensive experience in the micro tunneling domain with TBM manufacturers, including manufacturers in Japan and Germany. Projects included the first worldwide crossing of an active runway. No problems were encountered with either TBM manufacturing support or maintenance.

### 2.2.3 Maintenance, Repair, and Rehabilitation

#### *2.2.3.1 Maintenance Issues Related to Age*

At the top of the tunnel owners' list of regularly encountered maintenance issues that can be attributed to age are defective and obsolete tunnel M&E system elements and difficulty in finding replacement parts for the original equipment. Other issues include:

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

Electrical and wiring system degradation can be avoided with better design, components, and installation.

**AKDOT&PF:** The only age related issues of the 50-year-old Whittier Tunnel, which was rehabilitated over nine years ago, involve the portal doors. The current doors have a 50,000-cycle life expectancy, or approximately 5.5 years. Maintenance has allowed the AKDOT&PF to keep the doors operational for eight years. Currently AKDOT&PF is in the process of replacing the doors with one-million-cycle doors, which will increase life span and reliability.

**Caltrans:** Caltrans has documented vehicular tunnel inspection criteria for M&E features. Twelve tunnels are inspected for M&E equipment operation. The types of equipment in these tunnels vary and include:

- Ventilation equipment and control systems
- Tunnel lighting equipment and control systems
- Drainage equipment
- Traffic control equipment
- CO monitoring and control systems
- Fire/life-safety and security systems
- Fire-control hydrants and piping systems
- SCADA and communications systems

Eight tunnels are inspected only for CO monitoring and control system, tunnel lighting equipment and control systems, and fire-control hydrants and piping systems.

Regularly encountered maintenance issues that can be attributed to the age of the tunnels are:

- Lighting fixtures are difficult to relamp and keep clean; they are being replaced with modern fixtures with increasing frequency.
- Structure wall cleaning strategies are difficult because of washing equipment and wall surface obstructions.
- Keeping CO monitoring and environmental air quality measuring sensors operating and calibrated is maintenance intensive.
- Ventilation fan motor drive equipment and plenum dampers are cumbersome to adjust and maintain.

**Colorado DOT:** EJMT maintenance issues that are regularly encountered and that can be attributed to the 30 year plus age of the tunnels are having difficulty in finding replacement parts for the original equipment, keeping the air ducts free of dust accumulation, maintaining drain pipes and culverts surrounding the facility, and dealing with electrical system and wiring degradation. In addition, light fixtures were an ongoing difficulty until recent upgrades were made.

To date CDOT has had minimal failures of electrical equipment related to the 20-year-plus age of the HLT and RCT.

**District DOT:** In the early 1990s DDOT did major rehabilitation of its 30- to 40-year-old-tunnels. Age-related maintenance issues include:

- Ventilation and lighting equipment
- Broken fire mains – These are very expensive to repair as the fire main is buried between the tunnel and the surface. DDOT also has no control over the operation of isolating valves, which are operated from the surface.
- Hydrants – All hydrants are in service, but their age makes sourcing replacement parts difficult. Upgrading the hydrants to a modern design would be a reasonably sized project.
- Delaminated ceramic tile – Patch repairs are extremely expensive.
- Expansion joints – Generally speaking, once a tunnel starts leaking the ingress cannot be stopped; therefore, the focus should be on controlling the ingress, not stopping it. Drainage design should take into account the future requirement to collect water ingress piped to the base of the walls when waterproofing eventually fails.
- Ventilation fans – Motors were recently overhauled and bearings replaced on all fans. Chain drives were replaced under the major rehabilitation in the early 1990s and are beginning to show signs of failure. Total replacement of the chains should be expected in the next three to five years. A trial is currently in progress to test the conversion of the fans from chain drive to belt drive. One fan has been converted and is operating well. DDOT is in the process of working through the life-cycle cost analysis.
- Obsolescence of electronic components:
    - The programmable logic controller (PLC) was recently upgraded. The old PLC was installed in the early 1990s and was operating reliably, but the hardware was obsolete.
    - Fiber optic message signs are obsolete. Two signs were recently upgraded to light-emitting diode (LED) signs that are compatible with National Transportation Communications for Intelligent Transportation Systems (ITS) Protocol.

**MassDOT:** The Sumner and Callahan Tunnels, bored under the harbor, are MassDOT's oldest tunnels. Concrete liner delamination, fireproofing flaking off, keeping roadway leakage away from electrical components, and deteriorated decks requiring replacement are all maintenance issues. In general, liner decay, infiltration, electrical corrosion, and deck and drainage problems are maintenance issues encountered as MassDOT tunnels age.

**PennDOT:** PennDOT's most common tunnel maintenance issues are leaking wall joints, concrete spalling and delamination, conduit support failure, tunnel ceiling near failure, and M&E issues. Examples include:

- Squirrel Hill – Ice forms in the inbound lanes due to leakage.
- Ft. Pitt – Both inbound and outbound lanes have leaking walls.
- Liberty Tunnel – The ceiling leaks when it rains, ice is a problem in winter, and debris falls from the 200-foot-high airshafts in the center of the tunnel.

The most common PTC tunnel maintenance issues are water infiltration, concrete deterioration, tile delamination, and ceiling slab concrete and support deterioration.

**PANY&NJ:** Regularly encountered maintenance issues that can be attributed to the age of the PANY&NJ tunnels include sections of the fire standpipe system that were not replaced as a part of recent capital projects often develop leaks during winter months. In addition, stairwells inside the ventilation buildings are starting to deteriorate, and the underside roadway slabs are exhibiting some deterioration due to moisture.

**VA CBBT:** The 45-year-old CBBT has delaminated concrete maintenance issues.

**VDOT:** Age related maintenance issues of VDOT tunnels are pipe failures, waterproofing failures, and general corrosion.

**WSDOT:** Major issues of the I-90 tunnels that can be attributed to age include defective and obsolete tunnel M&E system elements and issues with tunnel leaks. Replacement parts for some of the M&E systems are unavailable, including parts for central processing units; program logic controllers, distribution breakers, and switchgear; and valve station actuators and gaskets.

#### *2.2.3.2 Maintenance Effectiveness in Decreasing Age Related Issues*

In general, tunnel owners are finding that age related maintenance needs are increasing regardless of maintenance strategy. They believe that their current maintenance program is effective, although ensuring adequate maintenance funding is an issue.

**AKDOT&PF:** AKDOT&PF considers its current maintenance program to be very effective.

**Caltrans:** Caltrans' equipment maintenance issues, money, and resources are always increasing, regardless of the maintenance effort. In general, relamping projects, SCADA upgrade projects, and ventilation fan drive rehabilitation projects are keeping up with maintenance repairs, technology advances, and rehabilitation projects.

A group of Caltrans tunnel structures fits the definition of tunnel (with equipment for fire/life safety) but have no CO environmental and air quality demand to activate the ventilation equipment. These structures receive a lower priority for maintenance resources; on the other hand, they do not require as much ongoing maintenance. Discussions are ongoing with local maintenance staff regarding code enforcement and liability versus effective use of limited maintenance resources.

**Colorado DOT:** CDOT maintenance has been successful, although eventual replacement of most systems is inevitable. To help minimize downtime, CDOT has taken a proactive approach to replacing some of the equipment as it reaches its life expectancy. It has also employed the use of a maintenance management program to aid in performing preventive maintenance and regular inspections on all its equipment and systems. By performing regularly scheduled maintenance, CDOT has been able to identify minor defects before they become major, thus prolonging the life of the equipment.

**District DOT:** DDOT maintenance strategies have reduced or at least kept in check the age related tunnel maintenance issues.

**MassDOT:** MassDOT issues Preventive Maintenance Work Orders and Corrective Maintenance Work Orders via its maintenance management information system (MMIS). The Corrective Maintenance Work Orders describe the work packages needed to fix or repair identified deficiencies, including routine repairs due to normal wear and tear or accidents. Both types of work orders are in general increasing each year due to the increase in the number of facilities. The current estimated cost to maintain the tunnels is $1.7 million each year for every lane mile.

**PennDOT:** PennDOT's tunnel maintenance budget of $6 million a year allows it to wash the tunnels every three weeks and check electrical and mechanical equipment monthly. It has planned a capital investment of $61 million for Liberty and $50 million for Squirrel Hill and spent $20 million for Ft. Pitt in 2002. Routine and in depth inspections are identifying conditions that are prioritized against PennDOT's maintenance budget, which allows it to keep up with operational needs.

**PANY&NJ:** The PANY&NJ believes it has adequate funding for its tunnel maintenance strategies. The maintenance issues, money, and resources are being monitored and are not changing dramatically.

**VA CBBT:** The CBBT District is performing an adequate amount of maintenance, allowing items to be replaced as they wear out instead of when they fail. The CBBT District believes that this practice is crucial. However, even with good maintenance and adequate resources, a 45-year-old structure will require an increasing amount of maintenance over time.

**VDOT:** Maintenance strategies have not decreased VDOT's maintenance effort, regardless of the resources expended.

**WSDOT:** WSDOT deals with issues of obsolescence by installing used parts or swapped parts from other equipment. Adequate maintenance funding and resources are issues for WSDOT.

#### *2.2.3.3 Definition of Good Repair and the Process for Deferral of Maintenance*

Tunnel owners define good repair as being fully operational without the need for continual repair and lasting 15 to 20 years at a minimum for large repair projects. Many tunnel owners must defer maintenance due to budget or other issues and evaluate priorities and risks to not defer maintenance on items that affect life safety.

**AKDOT&PF**: AKDOT&PF defines good repair as a repair that is at or better than the original installation. It has some deferred maintenance, but only on non-critical items or those that do not affect safe operation of the facility.

**Caltrans:** Caltrans is always deferring maintenance due to budget or other issues, evaluating priorities and risk analysis are constant concerns, and Caltrans walks a fine line when fighting for resources. Inspection reporting and attention to effective recommendations for maintenance is an art form. Inspection reporting must report the facts and market the work to be done to communicate the need, urgency, and ramifications of "put off for now."

**Colorado DOT:** CDOT defines good repair as a fully operational system without deficiency. Routine maintenance is not deferred due to budget. Major capital improvements to systems, however, are deferred.

**District DOT:** DDOT does not defer maintenance of assets with risk to the public. It established asset condition standards in the performance-based contract. Good repair is defined by the performance standards specified in the contract.

**MassDOT:** This is an open ended question. MassDOT Tunnel Inspection and Testing policy requires that all life-safety systems be fully tested and verified as functional for various emergency modes once every six months as a minimum (local fire codes require more frequent inspection and testing for some systems). Malfunctioning life-safety systems are repaired or replaced as soon as possible, preferably with original equipment manufacturer components, to maintain consistent, standardized maintenance procedures. Maintenance is performed based on a rigorous preventive maintenance schedule dictated and recorded by an asset management system for these systems. So far, maintenance is keeping up with the decay rate; however, a trend of increased corrective work orders issued versus time can be observed. Historical trends from some of the older MassDOT tunnels indicate a need to dedicate $1.7 million for every lane mile of tunnel structure every year, with significant variation depending on complexity. Items that are not deemed critical life-safety systems (e.g., structure conditions, pavement, wall appearance, and certain traffic appurtenances) are deferred as long as practical when budget constraints are imposed.

**PennDOT:** PennDOT defines good repair as something that will last 15 to 20 years.

**VA CBBT:** The CBBT District does not believe that a general definition of good repair can be applied to the vast spectrum of items. Each item is judged on its own merit, with the best safe, reliable, and cost effective result sought. Large procurement repair projects and replacement projects are typically expected to have at least a 20-year lifespan.

**VDOT:** VDOT defines good repair as repaired systems that function correctly. Due to limited budget, issues are prioritized and monies are allocated based on the priority.

**WSDOT:** WSDOT defines good repair as systems that function appropriately without continual need for repair. WSDOT does defer maintenance. In general, systems that are beyond their life-cycle are not replaced if they continue to function. For routine maintenance, fire and life-safety items are maintained and repaired before other, less essential items (e.g., a mechanical system that functions with a minor leak may be deferred).

Major system rehabilitation is covered under the WSDOT Program P3, which funds its preservation projects to extend the service life of existing assets. For this program, major M&E systems are prioritized for rehabilitation based on need. Systems that impact public and personnel safety if they fail are given the highest priority for rehabilitation or replacement. Other factors for prioritization include imminent failure of a system; components that are obsolete and not regularly manufactured; components that are deteriorated, defective, or damaged beyond repair for routine maintenance; and excessive maintenance cost to continually maintain a system.

#### *2.2.3.4 Most Significant Tunnel Maintenance Problem*

The biggest maintenance problems that tunnel owners have include maintenance accessibility while minimizing traffic disruption, obtaining components for obsolete electrical and mechanical systems, water leaks and drainage, structural and electrical system corrosion, lighting and ventilation, tile replacement, portal doors, damage from over-height vehicles, and maintaining fire extinguishers.

**AKDOT&PF:** The portal doors.

**Caltrans:** Water, moisture, and particulates; rodents; maintaining reflectivity of the lining surface for lighting, tile replacement, and lining painting; drainage.

**Colorado DOT:** Keeping seep-collection piping free of mineral and scale deposits, maintaining extensive amounts of heat tracing in the water lines, and maintaining ventilation fans with good belts and bearings. The HLT has had issues with vertical lift doors over the years; this has been reduced by making some changes to the balance and drive systems.

**District DOT:** Accessibility is a major problem, particularly on the I 395 corridor, where setting up temporary traffic control is dangerous and time consuming. In addition, damage from over-height vehicles is a major problem.

**MassDOT:** The biggest maintenance problem for the CA/T is corrosion of conduits and electrical systems within the traffic and exhaust areas of the tunnels. Water intrusion is a vexing issue as well.

**PennDOT:** Leaks are by far the highest root cause of all tunnel deficiencies.

**PANY&NJ:** Corrosion of the reinforcement cover and embedded roadway beams and ring leakage at the vent shafts.

**VA CBBT:** Corrosion.

**VDOT:** Corrosion.

**WSDOT:** For WSDOT, the biggest problem in the existing I-90 tunnels is aging equipment. Specifically, obtaining electrical and mechanical system components is a problem due to the lack of parts for obsolete systems. Maintaining fire extinguishers is also very time consuming.

#### *2.2.3.5 Concrete-Lined Tunnel Repair and Rehabilitation*

The tunnel owners have completed a number of significant repairs to or rehabilitation of their concrete lined tunnels. They have

- Replaced interior lining during off hour closures
- Repaired delaminated concrete and tiles, replaced wall tiles with panels, and replaced lighting during off hours and nights with single lane closures and at least one lane remaining open at all times
- Resurfaced concrete roadways and replaced ceiling slabs during multiday closures with two-way traffic in the adjacent bore
- Replaced ceiling slab using shotcrete and cast in place concrete during off-peak traffic shifts to adjacent tube
- Installed troughing to capture water entering through expansion joints and carry it to the wall to be piped into the ventilation shaft drainage system
- Replaced fire standpipes during off hour closings

**Caltrans:** Caltrans has replaced some interior lining at the Posey Tube using off hour closures.

**Colorado DOT:** CDOT has replaced wall panels, lighting, a portion of the high-voltage switchgear, and all high-voltage transformers in both EJMT bores. It has also cleaned the air ducts in both bores. All of this work was performed during off hours with a single lane closure, with the exception of the switchgear work, which was performed during normal working hours without a lane closure. Concrete roadway resurfacing required the closure of one bore with a two-way traffic operation in the opposite bore for a five day period.

The HLT had a crack in the ceiling slab over the eastbound traffic lanes (part of the building). The eastbound bore was closed from March to November while contractors repaired the slab with a steel reinforced 12-inch-thick concrete pour on top and steel reinforced 6-inch-thick shotcrete on bottom to “sandwich” the slab.

**District DOT:** DDOT has done a number of repairs to its concrete lined tunnels:

- Tile replacements are done with off hour closures.
- Maintenance and rehabilitation are usually performed during off hour closures. The only exceptions are the very small tunnels with an alternate route straight over the top of the tunnel. The smaller tunnels are sometimes closed at night in one direction but are always reopened prior to the morning peak.
- Repair of delaminated ceramic tile was a significant undertaking. Only delaminated areas were repaired, as opposed to 100 percent replacement. In most cases, the delamination occurred between the structural concrete and the bedding layers of mortar; in most places, the tiles were soundly bonded to the mortar.

- Leaking expansion joints were injected with hydrophilic polyurethane resin. While this was effective in the short term, after a cycle of expansion and contraction many joints started leaking again. Where practicable, troughing was installed to capture water entering through expansion joints. The trough carries the water to the wall, where it is piped into the ventilation shaft drainage system.
- Rehabilitation of damaged ceiling panels included recent placement of approximately 200 damaged concrete filled porcelain-coated panels. A total of 20,000 square feet of surface coating on concrete filled painted panels was recently repaired by applying a high performance epoxy coating.

**MassDOT:** MassDOT replaced the Sumner and Callahan Tunnels' ceilings and wall panels, both of which were originally made of cast in place concrete. The ceilings were replaced with suspended metal ceilings. Individual wall tiles were replaced with steel panels having a baked enamel finish.

**PennDOT:** PennDOT closes its tunnels for concrete repairs. The PTC's most significant issue is repairing/replacing concrete ceiling slabs, with off-peak traffic shifts to the sister tube.

**PANY&NJ:** The Holland Tunnel has had ceiling and fire standpipe replacements. The Lincoln Tunnel center tube has had roadway deck restoration with a cast in place composite slab. Rehabilitations were primarily done under off hour closings.

**VA CBBT:** The CBBT District has done standard delaminated concrete and tile repair during nighttime work, with one lane remaining open at all times.

**VDOT:** VDOT mountain tunnels had major rehabilitation using waterproof membrane, joint grouting, and non shrink structural concrete. Depending on the type of repair, VDOT re routed traffic to the parallel tube or used off hour lane closures under traffic.

### *2.2.3.6 Ventilation Systems*

Tunnel ventilation systems vary. Fully transverse ventilation systems with supply plenums below and exhaust plenums above are most common. Semi-transverse and longitudinal ventilation systems are also used. A number of tunnels have both supply and exhaust plenums above, and some have supply plenums on the sides and exhaust plenums above or both supply and exhaust plenums on the sides.

AKDOT&PF: Jet fans are the primary ventilation system. Their safe-house ventilation system has a duct below the roadway.

**Caltrans:** All of the older long tunnels have full transverse ventilation with a centrifugal fan in both portals and supply plenums below the roadway and exhaust plenums above the roadway. One has full transverse ventilation with axial vane fans in one portal and supply plenums and exhaust plenums above the roadway.[26] The newer tunnels have full transverse ventilation with axial vane

[26] Although this does not seem an effective design, with short circuiting probable, the existing tunnel's orientation and traffic direction do not seem to create air quality issues.

fans in one portal, supply plenums on the sides of the roadway, and exhaust plenums above the roadway. The newest tunnels (post-Memorial Tunnel fire demonstration project) have longitudinal ventilation with axial vane/silencer fans mounted in the structure.

**Colorado DOT:** The EJMT has a full transverse system in both bores, with a total of 28 fans. Electrical fan motors range from 12.5 to 600 hp. The Johnson bore supply fans each have a maximum capacity of 420,000 cubic feet per minute (CFM), and the bore's exhaust fans each have a maximum capacity of 460,000 CFM. The Eisenhower bore supply fans each have a maximum capacity of 533,000 CFM, and the bore's exhaust fans each have a capacity of 542,000 CFM. In maximum "fire mode," six vent fans can be run on 600 hp in each ventilation building. The EJMT has supply and exhaust plenums above the roadway; no plenums are below the roadway.

The HLT has eight axial flow fans, four for each bore. Each fan is 300 hp and is capable of pushing up to 238,000 CFM. The HLT plenums are above each roadway.

**District DOT:** The Mall and Air Rights Tunnels use transverse ventilation using air plenums along the walls to supply and exhaust the air. The 9th Street Tunnel uses semi-transverse ventilation using supply fans. The 12th Street Tunnel uses longitudinal ventilation with dual points of extraction.

**MassDOT:** MassDOT ventilation systems vary. Most have supply plenums below the roadway and exhaust plenums above the roadway; some plenums are along the sides. Some areas have no plenums at all and are longitudinally ventilated using intake and/or extraction ports or use jet fans only.

**PennDOT:** PennDOT tunnels have electric motors supplying the air and exhaust fans. All supply and exhaust plenums are above the roadway. The PTC tunnels have semi-transverse ventilation with overhead supply plenums, except for the Lehigh #2 Tunnel, which has longitudinal jet fans.

**PANY&NJ:** The PANY&NJ has fully transverse ventilation systems in its tunnels, with supply plenums below the roadway and exhaust plenums above the roadway.

**VA CBBT:** The CBBT has fully transverse ventilation systems, with supply plenums below the roadway and exhaust plenums above the roadway.

**VDOT:** VDOT has two semi-transverse and four transverse ventilation systems for its Tidewater tunnels and transverse systems for its mountain tunnels. The Tidewater tunnels, except for the Eastbound Downtown Tunnel, have supply plenums below the roadway and exhaust plenums above the roadway. The mountain tunnels use only overhead plenums.

**WSDOT:** The existing I-90 tunnels have a fully transverse ventilation system with exhaust and supply plenums above the roadway. The proposed SR 99 tunnel is planned to have a semi-transverse single point extraction system with an exhaust duct on the side of the roadway.

#### *2.2.3.7 Maintenance of Devices in Tunnel Environment and with Tunnel Washing*

The tunnel owners handle the maintenance of devices (i.e., fire alarm pull stations, exit lights, and emergency strobe lights) in the tunnel environment and tunnel washing in a variety of ways. They purchase components that can withstand multiple washings and corrosive environments, such as stainless steel devices and plastic housing for fire alarm pull stations. Devices are tested weekly or monthly and repaired as needed. Some tunnel owners perform maintenance at night with the tunnel closed. Some use in-house staff, while others use performance-based asset management contracts.

**AKDOT&PF:** The AKDOT&PF devices are tested monthly and repaired as needed. Washing is conducted monthly.

**Caltrans:** All interior tunnel maintenance is done at night with the tunnel or tube closed.

**Colorado DOT:** CDOT takes no special precautions.

**District DOT:** A private contractor maintains all M&E assets and systems under a performance-based asset management contract. Some structural elements are included in the scope of the asset management contract. The asset management contractor's internal resources perform routine maintenance of devices such as emergency phones, fire-detection and alarm systems, CCTV systems, CO analyzers, and control systems. Where necessary, the prime contractor uses specialist subcontractors for the provision of services such as annual certification of fire-detection and alarm systems and calibration of CO analyzers. Subcontractors are also used for major rehabilitation activities such as ceiling panel rehabilitation and ventilation fan rehabilitation.

**MassDOT:** In-house MassDOT staff maintains these devices. Most of these fixtures have been replaced or specified new as mining grade or explosion proof and are able to withstand multiple washings and corrosive environments. Conduit corrosion leading up to the devices remains problematic.

**PennDOT:** PennDOT maintains the devices once a week and runs the emergency system once a month. It also has regular in-house servicing, supported by contract repair services.

**VA CBBT:** The CBBT District uses 316 marine grade stainless steel and follows NEMA 4 for electrical maintenance.

**VDOT:** If devices are damaged, VDOT completes the repairs internally.

**WSDOT:** WSDOT has installed plastic housing for fire alarm pull stations at the existing I-90 tunnels to address issues it was having with ground faults. It has also switched out existing static hinged signs with special triangular signs because of issues related to hinge maintenance.

#### *2.2.3.8 Frequency of Tunnel Washing*

Tunnels are typically washed at least four times a year, and more as needed depending on weather and traffic. Some urban tunnels are washed every week or two during overnight hours. See Figure 2.2 for examples of tunnel washing equipment**.**

**AKDOT&PF:** Only the safe house and portal structures are washed regularly. The rest of the structure is rock.


**Figure 2.1** ***Examples of equipment used to wash tunnel walls***

**Caltrans:** Caltrans does not have a predetermined wash schedule. Washing is done on an as needed basis, on demand, or as a result of complaints.

**Colorado DOT:** CDOT is limited in its ability to wash its tunnels due to extremely cold temperatures for most of the year. It washes once in late spring and once in early fall. The HLT and RCT are washed quarterly, weather permitting, with a pressure wash on the warmer days during the colder months.

**District DOT:** DDOT washes its tunnels at least four times a year. Walls and ceilings are currently cleaned three times a year (in August, December, and March). Walls in tunnels with very high traffic volumes are washed two additional times (in June and October).

**MassDOT:** MassDOT tunnels are washed from late spring to early fall depending on traffic volumes, truck volumes, and grade, all of which contribute to dirt accumulation. Busy uphill grade areas are washed every two weeks, whereas low-volume areas are washed closer to every eight weeks.

**PennDOT:** PennDOT washes its tunnels at least eight times each year, as weather and traffic permit.

**PANY&NJ:** The Holland Tunnels are washed weekly, and more often as required. The Lincoln Tunnels are washed regularly, based on availability and construction and maintenance activities. Tunnel washing is done during overnight hours only and is minimized during winter months.

**VA CBBT:** The CBBT District schedules its tunnels to be scrubbed once every six weeks.

**VDOT:** VDOT washes its tunnels four times annually in the Hampton Roads District and two times annually in the Bristol District.

**WSDOT:** WSDOT washes its tunnels once a month or as needed. The tendency is to wash the tunnel walls more often in the winter.

#### *2.2.3.9 Maintenance Workforce*

Most tunnel owners perform regular maintenance with in-house forces and use consultants for specific tasks. Some tunnel owners perform all maintenance with consultants. Others use a mix of in-house and consultant staff for regular maintenance and on-call contractors for specialty and emergency repairs.

**AKDOT&PF:** The contractor performs all AKDOT&PF tunnel maintenance. Maintenance personnel are on duty during all open hours and perform repairs after hours. Personnel are on-call 24/7.

**Caltrans:** Regular maintenance is performed in-house.

**Colorado DOT:** All maintenance activities are handled in-house, except for major improvements, which are performed by contractors and consultants.

**District DOT:** A dedicated private contractor performs maintenance under a performance-based asset management contract. Where necessary, the prime contractor uses specialist subcontractors.

**MassDOT:** MassDOT in-house forces perform regular maintenance. Consultants are used for specific tasks, such as tunnel inspection.

**PennDOT:** PennDOT uses a contractor for major electrical maintenance and capital improvements. In-house forces perform all other work: washing; minor and moderate electrical repairs; and mechanical preventive maintenance checks, tests, and repairs. The PTC uses preventive maintenance service contracts for electrical control, monitoring, and alarm systems.

**PANY&NJ:** In-house staff handles most of the Holland Tunnel maintenance activities, with the exception of garbage removal, which is handled through an outside contractor. Contractors must go through a security check before working on tunnels.

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

**VA CBBT:** The CBBT District uses in-house forces for maintenance activities. For all others it uses the Virginia Procurement System, unless it is an emergency repair. For emergency repairs, the CBBT District has proven companies that have demonstrated their capabilities and ability to respond quickly.

**VDOT:** VDOT uses a combination of in-house forces and outside contractors. It does not currently have an on-call contract for tunnel maintenance in the Hampton Roads District. The Bristol District has an on-call electrical contract in place.

**WSDOT:** WSDOT generally handles maintenance activities in-house, although it has had small outside on-call contracts. WSDOT does have a minor contract to support tunnel phone and ITS. It also has a maintenance contract for its VAX system.

#### *2.2.3.10 Mechanism to Maintain, Debug, and Troubleshoot Operation Software Systems*

To maintain, debug, and troubleshoot operation software systems (i.e., maintenance contract, in-house, or other), tunnel owners typically use in-house staff. Some regular and on-call maintenance contracts are used.

**AKDOT&PF:** The software is maintained under contract. In addition, the redundant systems compare with each other for proper function; any failure triggers maintenance action.

**Caltrans:** Done in-house.

**Colorado DOT:** The EJMT does this in-house. The HLT has a maintenance contract for the SCADA system; all other systems are maintained in-house.

**District DOT**: The prime contractor for DDOT's Asset Management contract works with specialist subcontractors to troubleshoot, diagnose, and repair software and hardware problems in control systems. The prime contractor typically repairs or replaces field devices. A specialist subcontractor repairs and replaces PLC hardware and software.

**MassDOT:** MassDOT uses a maintenance contractor.

**PennDOT:** PennDOT utilizes in-house electricians. Maintenance and preventive maintenance contracts are used if needed.

**PANY&NJ:** Handled through the PANY&NJ Technology Services Department.

**VA CBBT:** The CBBT District uses in-house forces.

**VDOT:** VDOT does not have any operations software systems at this time.

**WSDOT:** WSDOT mostly uses in-house forces. It does have an on-call contract for its existing fire-control system.

#### 2.2.3.11 Timing of Maintenance Activities

The tunnel owners perform tunnel maintenance such that traffic disruption and closures are minimized. Most maintenance work is conducted during off-peak hours and overnight with lane closures. Maintenance work is performed as weather permits during winter months.

**AKDOT&PF:** Most maintenance is conducted after hours and between alternating releases, or consists of activities that do not disrupt traffic.

**Caltrans:** Inside tunnel maintenance is done only at night with closure. Portal maintenance is done 24/7.

**Colorado DOT:** CDOT weekend and holiday maintenance requiring a lane closure is prohibited because weekends and holidays are its busiest times. Weekday maintenance is allowed early in the morning or during the late evening. If queuing occurs during these periods, the work is ended.

**District DOT:** DDOT contract documents specify that lane closures may be implemented at the following times:

- Weekdays: 9:30 a.m. to 3:30 p.m.
- Weeknights: 7:30 p.m. to 4:30 a.m.
- Weekends: no work permitted without prior approval of the chief engineer

Generally speaking, the available window for maintenance work during the day is so small that it is difficult to use the time productively. Daytime closures in the center of DC typically create high levels of congestion. For these reasons, the contractor performs the vast majority of lane closures between 8 p.m. and 4:30 a.m.

Maintenance is performed in plant and equipment rooms during the day where access is possible without the need for temporary traffic control. Seasonal constraints are not imposed contractually; during winter months, the scope of work that can be performed is dictated by climatic conditions. Tunnel washing, for example, is difficult to manage during the winter months.

**MassDOT:** Due to the urban setting of its tunnels, MassDOT requires that most maintenance work be done at night to limit traffic disruption. Maintenance activities are coordinated and scheduled to minimize closures.

**PennDOT:** Washing is done in temperatures above freezing. Concrete repairs need to be done in temperatures above freezing, in general from April through October. Electrical tunnel maintenance is completed during nighttime hours. All interior tunnel work is performed by shutting down one of two lanes inside the tunnel to work on the closed lane.

**PANY&NJ:** Holland Tunnel maintenance inside the ventilation building and service garages occurs weekdays (i.e., Monday through Friday). Maintenance work inside the tunnels at roadway level occurs during the overnight period with lane closures.

Lincoln Tunnel routine maintenance activities involving tunnel lane closures are performed during the overnight hours to minimize traffic impacts. Emergency repairs are conducted as needed. Tunnel washing is minimized during winter months due to freezing temperatures.

**VA CBBT:** The CBBT District allows tunnel maintenance only at night while leaving one lane open; standard holiday restrictions apply. At times, depending on the type of work, temperature can be a limiting factor. As an example, many products can only be applied at a 50°F and rising surface temperature.

**VDOT:** If roadway access is required, VDOT requires maintenance work to be done during off-peak evening hours; otherwise, it can be done anytime.

**WSDOT:** WSDOT maintenance work that cannot be completed during the day is completed off-peak from 11 p.m. to 5 a.m. Routine maintenance is completed on Thursday, starting at about 2 a.m. Once a year, WSDOT has a tunnel closure for maintenance work. It also completes work during special events when the highway is closed for other purposes, such as the Sea Fair event.

#### *2.2.3.12 Capacity of Maintenance Yard Facilities*

Urban tunnel owners typically have sufficient maintenance yard facilities. In some cases, maintenance yards are limited, impacting productivity and the ability to garage specialty automotive support equipment.

**AKDOT&PF:** The Whittier Tunnel has plenty of room for maintenance yard facilities since it is not an urban tunnel.

**Caltrans:** Caltrans maintenance yard facilities are adequate. Office and storage spaces for parts, materials, and tools could use improvement.

**District DOT:** DDOT maintenance yard facilities are adequate; the contractor maintains its own office and storage facility close to the tunnels. The contractor also stores maintenance vehicles in a vacant auxiliary space in one of the two main tunnels.

**MassDOT:** MassDOT has a central maintenance facility where about 90 percent of its tunnel maintenance services are provided. The central maintenance facility is the second largest, with approximately 90 people reporting there.

**PennDOT:** PennDOT maintenance yard facilities are adequate.

**PANY&NJ:** The Holland Tunnel maintenance yard facilities are adequate. The Lincoln Tunnel maintenance yard support areas are extremely tight and limited, which impacts its productivity and ability to garage its specialty automotive support equipment.

**VA CBBT:** The CBBT District has adequate storage areas for work done on its facility.

**VDOT:** VDOT has adequate maintenance yard facilities because these areas were included as part of the tunnel design.

**WSDOT:** WSDOT maintenance yard facilities are adequate.

#### *2.2.3.13 Current "Best Practices"*

The tunnel owners consider best practice routine maintenance, repair, and rehabilitation activities to include:

- Using an MMIS that issues preventive maintenance work orders and tracks corrective work orders
- Holding an annual walk through with emergency personnel
- Installing a lane control signals system in tunnels without lane control
- Taking monthly manual measurements of vibration in tunnels with ventilation equipment that

is not fitted with real-time temperature and vibration monitoring systems

- Running generators with a load on them monthly
- Washing tunnels regularly
- Adding air with the soap in wash trucks so that the soap stays on the walls longer
- Using hydro-demolition to remove deteriorated concrete
- Performing high-pressure cleaning of seep lines
- Changing tunnel light bulbs when 10 percent are out of service or relamping once a month
- Checking emergency systems monthly
- Phasing rehabilitation projects so that they are affordable considering other needs and upgrading life-safety systems during the rehabilitation
- Using night and weekend work for high average daily traffic (ADT) tunnels

**AKDOT&PF:** AKDOT&PF considers its preventive maintenance to be top notch. Most systems on site affect safety; it is, therefore, important that they function on demand.

**Caltrans:** Caltrans considers its scheduled and as needed inspections and mechanical preventive maintenance and repairs to be best practice.

**Colorado DOT:** CDOT considers its best practices to be its high pressure cleaning of seep lines and its routine loading of generators.

**District DOT:** DDOT believes that owners and operators of existing tunnels designed without lane control should consider the DDOT's recently installed system of lane control signals as an upgrade option. In addition, ventilation equipment not fitted with real-time temperature and vibration monitoring should have vibration measured manually each month, especially if the fans are older, such as DDOT's 40-year-old fans.

**MassDOT:** MassDOT has an MMIS in place that issues preventive maintenance work orders monthly, quarterly, semi annually, and annually as required by safety standards, codes, and manufacturer's recommendations. This system also tracks corrective work orders as required for repairs and deficiencies identified during the preventive maintenance process or inspection. In addition, MassDOT now adds air with the soap in its wash trucks so that the soap stays on the walls longer; the wash process is to spray, soak, and then brush.

**PennDOT:** PennDOT best practices include washing tunnels every two to three weeks, changing tunnel light bulbs when 10 percent are out of service, checking emergency systems monthly, and holding an annual walk through with the City of Pittsburgh emergency personnel. Based on its experience rehabilitating its tunnels every 10 to 40 years, PennDOT recommends that owners phase rehabilitation projects so that they are affordable, considering other needs; consider night and weekend work for high ADT tunnels; consider upgrades to life-safety systems during the rehabilitation; and use hydrodemolition to remove deteriorated concrete.

**PANY&NJ:** The PANY&NJ believes it is critical to follow manufacturers' recommendations for electrical and mechanical systems.

**VA CBBT:** The CBBT District best practices are using maintainers instead of sensors to check all electrical and mechanical aspects of the tunnel, relamping once a month, scrubbing tunnels once every six weeks, and checking the generator (i.e., run with a load put on it) once a month.

**WSDOT:** WSDOT's advice is to adapt proactive maintenance practices, set up maintenance schedules and adjust schedules as lessons are learned, and stick to manufacturers' suggested maintenance practices.

### 2.2.4 Inspection

#### *2.2.4.1 Inspection Frequency of Systems and System Components*

In general, tunnel owners have separate inspection frequencies for each system (e.g., structural, electrical, mechanical, and communications). The tunnel structure typically is inspected every two years. M&E systems are inspected more frequently, from daily informal inspections to monthly or annual in depth inspections. Some owners continuously monitor operational systems, such as lighting and communications. At least one tunnel owner prefers a risk-based inspection approach.

**AKDOT&PF:** AKDOT&PF has separate inspections for each item. The frequency is monthly structural inspections and daily rock inspections for safety. The manufacturers' recommendations are followed for all other items.

**Caltrans:** Operational systems, such as lighting and communications, are continuously monitored. M&E inspections are every 12 months, including equipment condition evaluation. Structural inspections are conducted at 24 month intervals. Defining a tunnel was prudent to enable Caltrans to effectively use tunnel inspection resources.

**Colorado DOT:** Informal inspections occur daily. The inspection frequencies initially were based on manufacturer recommendations. These frequencies were incorporated into the maintenance management system for scheduling preventive maintenance. Over the course of time and based on observations made while performing preventive maintenance, it was determined that some frequencies could be adjusted in order to provide a more efficient preventive maintenance schedule.

**District DOT:** DDOT has three quarterly inspections and an annual comprehensive inspection. Each inspection evaluates structural, mechanical, electrical, and lighting categories. Each category is scored based on asset conditions and the contractor's performance on time critical performance.

**MassDOT:** A 2007 inspection policy sets the frequency of inspections. In general, MassDOT inspection frequencies are full tunnel inspections every 36 months to dovetail with bondholder trust agreements, overhead items every 12 months, special members every three to six months, life-safety systems every six months, and ventilation testing every six months. Rather than mandating specific inspection intervals, MassDOT prefers a risk-based inspection approach that takes the complexity and self weight versus traffic loading into account. Components that receive a rating of 4 (poor condition) are inspected every 12 months except for overhead components, which are inspected every six months. Components that receive a rating of 3 (serious condition) are inspected every six months except for overhead components, which are then inspected every three months.

**PennDOT:** PennDOT does NBIS inspections every two years. In depth inspections are performed prior to rehabilitation. M&E checks are done daily to monthly.

**PANY&NJ:** A structural inspection is performed every two years with consultant and in-house personnel. Settlement surveys were previously done every year; for the past 10 years they have been done every two years. The PANY&NJ also has facilities staff that do electrical and mechanical inspections.

**VA CBBT:** The entire tunnel is walked once annually. Half the upper and lower air ducts are walked each year so that they are completely done once every two years.

**VDOT:** VDOT inspects all its tunnels at the same time.

**WSDOT:** The WSDOT Bridge Preservation Office is not involved with the communications systems. WSDOT has different inspection frequencies for structural inspections based on structure type (i.e., timber, concrete lined, rock, lids, or bored). There is no specified program for the Bridge Preservation Office to perform mechanical or electrical inspection.

#### *2.2.4.2 Inspection Documentation and Tracking*

Tunnel owners use various methods to record and keep track of tunnel inspections, including deficiencies. Some document deficiencies in their inspection reports and track them in databases. Others use their maintenance management systems to track tunnel inspections and document findings and corrective actions. Still others record tunnel inspection information on bridge inspection forms and track them in their BMSs.

**AKDOT&PF:** Records are stored in a database and any changes are noted for action.

**Caltrans:** For the general inspection, Caltrans uses its BMS. All tunnels are inventoried in the same manner as the bridges. Deficiencies found during a general inspection are noted in the Bridge Inspection Report and kept in the database. M&E work recommendations are added to the Integrated Maintenance Management System. M&E reports are written for each structure, distributed to the local maintenance district, and archived in the same way as the structural reports.

**Colorado DOT:** The EJMT had its electrical and mechanical systems inspected in 2006 and a structural integrity inspection in 2008. The HLT had a baseline structural integrity inspection in 2009 and uses a maintenance management system to keep track of when inspections are due as well as to document findings and any corrective actions taken.

**District DOT:** DDOT catalogues inspection results in an MS Excel spreadsheet created for the purpose. Deficiencies are documented in a punch list to be addressed by the contractor.

**MassDOT:** MassDOT developed its tunnel inspection forms from its existing bridge inspection forms. The main tunnel components were categorized as an extension of Item 62, Culvert (e.g., Item 62c is ceiling, overhead, and exhaust ducts). In its first field inspection using the draft forms, it inventoried all tunnel components and categorized the various tunnel sections; several iterations of the forms were required. Immediate action items are addressed during field inspections (e.g., loose concrete or fireproofing and loose nuts). The inspection reports are reviewed and forwarded to MassDOT Maintenance. Corrective work orders are issued through the MMIS and placed into the capital program for eventual incorporation into a construction contract.

**PennDOT:** PennDOT records inspection information with bridge inspection forms and enters data into Bridge Management System 2 and TMS reports. The PTC uses digital and hard copy reports that are being recompiled into the OneDOT system, with future data collector field options.

**PANY&NJ:** A report is written with recommended repairs classified as priority, routine, or safety. All immediate conditions are repaired during the inspection. All priority repair recommendations are assigned a tracking number.

**VA CBBT:** The CBBT District's third-party engineering consultant provides annual reports.

**VDOT:** Inspection reports are prepared for each inspection and multiple copies are kept on file.

**WSDOT:** Inspections are recorded and tracked through WSDOT's mobile bridge laptop inspection program.

#### *2.2.4.3 Inspection Program Manuals*

Tunnel owners have used various manuals to develop their tunnel inspection program, including internal inspection, maintenance, operations, and facility management manuals and policy directives; technical equipment manuals; manufacturers' manuals; NFPA 502; the 2005 FHWA *Highway and Rail Transit Tunnel Inspection Manual*; and various industry guidelines.

**AKDOT&PF:** Inspections are covered in the AKDOT&PF maintenance and operations manual, which provides the details on what should be examined and the process that should be used.

**Caltrans:** Caltrans uses technical equipment manuals, manufacturers' manuals, and established protocol for its tunnel inspection program. The *SM&I Procedures Manual* has some references to tunnels. M&E inspection procedures have no official manual. Each Caltrans inspector has personal documentation historical records for each structure and an average of 20 to 30 years of equipment inspection experience.

**Colorado DOT:** Manuals for the EJMT and proposed for the HLT include:

- 2005 FHWA *Highway and Rail Transit Tunnel Inspection Manual*
- *Guide for Making a Condition Survey of Concrete in Service*, ACI 201.1R

- *Nondestructive Test Methods for Evaluation of Concrete Structures*, ACI 228.2

**District DOT:** DDOT uses the following manuals for its inspection program:

- *FHWA Highway and Rail Transit Tunnel Inspection Manual*
- *Tunnel Management System*
- *Recommended Practice for Tunnel Lighting,* IESNA RP-22
- *Standard for Road Tunnels, Bridges, and Other Limited Access Highways,* NFPA 502

**MassDOT:** The MassDOT inspection program is governed by its 2007 "Tunnel Inspection and Testing Program" Policy Directive. It requires that the condition evaluation of tunnel elements be consistent with the MassDOT *Inspection Manual for Tunnels and Boat Structures*, Volume 5, November 2003; the FHWA 2005 *Highways and Rail Transit Tunnel Inspection Manual*; and various MassDOT Highway Operations Center (HOC; formerly the Operations Control Center) response plan documents.

**PennDOT:** PennDOT uses its BMS manual and the FHWA TMS manual to do tunnel inspections.

**PANY&NJ:** The PANY&NJ developed its own manual for tunnel inspections. The guidelines provide uniformity between inspections.

**VA CBBT:** The 2005 FHWA *Highway and Rail Transit Tunnel Inspection Manual* has been referenced in the past to provide guidance on inspection for the CBBT District tunnel projects. The CBBT District has also used NFPA 502, and the American Society of Heating, Refrigerating and Air Conditioning Engineers *Application Handbook* for guidance in tunnel inspection related to ventilation and life safety.

Additionally, the CBBT District sponsored a tunnel lighting assessment and study about 12 years ago that led to a tunnel lighting replacement project. Referenced manuals for testing the lighting and assessing the reflectivity of the tunnel walls, ambient lighting conditions, and other relevant factors included the IESNA publication RP 22 1996, *Standard Practice for Tunnel Lighting*, and applicable ANSI requirements.

**VDOT:** VDOT has used the FHWA *Highway and Rail Transit Tunnel Inspection Manual.*

**WSDOT:** WSDOT has not used a specialized manual. It has been performing "safety" level inspections of all its tunnels for more than 20 years. It uses the 2005 FHWA *Highway and Rail Transit Tunnel Inspection Manual* as a resource.

#### *2.2.4.4 Tunnel Segments for Inspection and Reporting*

Tunnel owners divide their tunnels into segments for inspection and reporting purposes. Segment lengths vary from 35 feet to 50 feet to 100 feet, with station numbers marked on the walls.

**AKDOT&PF:** The entire facility is divided into zones, which are logically designated by landmarks such as safe houses.

**Caltrans:** Caltrans divides into segments (e.g., east or west, Oakland/Alameda Stationing painted at intervals through the tunnel) as its primary method of identifying locations in tunnels. This is similarly done for M&E/operations inspections (east or west, Oakland/Alameda portal buildings).

**Colorado DOT:** For the EJMT, a 50-foot segment (associated with about eight 6-foot long precast panels) was used for designation.

**District DOT:** For inspection and recording purposes, DDOT has broken the tunnel into 50-foot increments. Station markers are attached to the walls for identification in the field.

**MassDOT:** MassDOT divides its tunnels into 225 inspection segments based on the tunnel structure type and geometry. MassDOT assigns an inventory number similarly to how it divides multi span bridges.

**PennDOT:** PennDOT uses 100 foot stations. The PTC uses sequential numbering of construction panels, which vary from 35 to 50 feet.

**PANY&NJ:** The PANY&NJ uses the existing stations marked on the tunnel walls.

**VA CBBT:** The CBBT District uses stations throughout the tunnel.

**VDOT:** The Hampton Roads District's tunnels are divided by station numbers, and the Bristol District's tunnels are divided into four sections.

**WSDOT:** The major WSDOT tunnels are broken up into smaller manageable units for inspection purposes.

#### *2.2.4.5 Procedures to Inspect Rock Tunnels with No Lining*

The tunnel owners use various procedures to inspect rock tunnels with no lining. Most do a visual drive through with close up inspections from truck mounted platforms for areas of concern. Some use light hammer sounding, rock cuts, and geophysical evaluations.

**AKDOT&PF:** The AKDOT&PF inspection involves lighting up the rock and conducting a slow drive through. Areas of concern are given a more thorough, up-close inspection from the bucket truck.

**MassDOT:** MassDOT does not have any rock tunnels.

**PANY&NJ:** The PANY&NJ uses rock cuts plus geophysical evaluations prior to and during a tunneling cycle.

**WSDOT:** WSDOT uses visual inspection only, with light hammer sounding of suspect areas. It always uses a truck mounted platform for access to the crown.

#### *2.2.4.6 Timing of Inspections*

Most tunnel owners allow inspections only at night or on weekends to limit traffic disruption and avoid the peak summer traffic season in tunnels that require inspection with traffic control. Some owners have no inspection limitations except for when major events are in the area, while some tunnels in cold climates have inspections only in the warmer months.

**AKDOT&PF:** AKDOT&PF has specific times when inspections must occur (e.g., before opening for the day).

**Caltrans:** Caltrans limitations on tunnel inspection include interior inspections at night, with most tunnel inspections in urban areas done at night. Limitations can also relate to personnel availability. It has no seasonal restrictions.

**Colorado DOT:** Both the EJMT and the HLT can have cold temperatures in unheated ceiling spaces; therefore, June through October is the best time for inspections. Since HLT roadway spaces need to be inspected with traffic control, peak summer traffic season (July through August) is avoided.

**District DOT:** DDOT has no limitations on when tunnel inspection can occur. However, as the tunnels are in Washington, DC, evaluations need to be scheduled to avoid major events, such as inaugurations, dignitaries' visits, and major sporting events.

**MassDOT:** MassDOT tunnel inspections are done at night with lane closures coordinated with other maintenance work.

**PennDOT:** Generally PennDOT inspections of tunnels on major routes are done at night or on weekends; tunnels on lesser routes are inspected during the day. PennDOT usually does the inspections in better weather (April through October), although it has inspected the Liberty Tunnel in late November to early December. The PTC does inspections with single lane crossover in the sister tube during periods when weather and traffic conditions permit.

**PANY&NJ:** Inspections are performed at night, during facility maintenance operations, and in the spring.

**VA CBBT:** The CBBT District has no limitations on when tunnel inspection can occur.

**VDOT:** VDOT limitations on when tunnel inspection can occur depend on the portion of the tunnel being inspected; it might be necessary to perform the inspection during non rush hour periods.

**WSDOT:** WSDOT limitations on when tunnel inspection can occur are both seasonal and time of day, depending on tunnel location.

### 2.2.5 Operations

#### *2.2.5.1 Integration of Operation Controls for Traffic and Support Facilities*

Most owners have integrated operation controls for traffic and support facilities (see Figure 2.3). Some owners have SCADA systems that allow access and control of functions in their other tunnels. At least one owner has an operations control center that is integrated for central monitoring and emergency notification, traffic management and response, facilities management, and security and work access coordination. Tunnel owners have various standalone systems, including fan-monitoring systems, traffic signal control systems, over-height vehicle monitoring systems, and fire-control systems.

**Figure 2.2** ***Integrated operations control centers***

**AKDOT&PF:** Only the operations system and traffic control are integrated. The support systems send signals that they are functioning or not, but they cannot be controlled from the operations panel. The fan monitoring system is standalone.

**Caltrans:** The SCADA system is used to view, monitor, and historically archive data from the various components of the tunnel, such as number of cars, CO levels, call boxes, and lighting levels. The SCADA also allows remote control of the fans and damper doors. The Caldecott Operations, Maintenance, and Control (OMC) Building SCADA computer will allow the operator to access and control all functions of the other tunnels in the District that will be connected via the Internet.

**Colorado DOT:** The two EJMT portals are traffic signal controlled using a CDOT designed PLC and fiber transceiver system monitoring over-height vehicles and signals controls. It is a standalone system to ensure maximum up time and immediate response without centralized dependencies. The HLT and RCT operation controls for traffic and support facilities are integrated.

**District DOT:** DDOT's only traffic control systems are lane signals, and they are standalone.

**MassDOT:** MassDOT's HOC is integrated for central monitoring and emergency notification, traffic management and response, facilities management, and security and work access coordination. The HOC has two fully redundant servers; two additional fully redundant servers are at the backup HOC and can be up and running in 20 minutes.

**PennDOT:** PennDOT operation controls for traffic and support facilities are integrated for fans, lights, fire alarm, microwave traffic detectors, over-height truck detection, CO monitoring, temperature sensors, and cameras. The PTC operation controls integration is variable by location. At the Lehigh County tunnel, lights, fans, heat, and motion are all integrated, but others are mostly standalone.

**PANY&NJ:** The traffic-related equipment and other facilities are on separate systems.

**VA CBBT:** The CBBT District has a SCADA system that controls message signs on bridge trestles approaching the tunnels. In addition, it has cameras in the tunnel that are monitored by operators.

**VDOT:** VDOT traffic and equipment control are integrated; all others are standalone.

**WSDOT:** In WSDOT tunnels, everything is integrated except the fire-control system.

#### *2.2.5.2 Measures to Reduce Operating Costs*

Tunnel owners are 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 and eliminating the scope of some contracts
- Reducing non-critical maintenance activities
- Reducing labor costs by reducing non emergency overtime
- Upgrading M&E components during rehabilitation projects
- Replacing lighting with more energy-efficient sources (e.g., replacing with LED lighting and installing motion sensors to ensure most of the 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
- Purchasing systems and equipment that can be maintained in-house
- Stockpiling parts from obsolete equipment

**AKDOT&PF:** The operating costs are contained. A reduction in operating costs would require changes in service or safety.

**Caltrans:** Caltrans is reducing personnel to reduce operating costs.

**Colorado DOT:** CDOT is performing energy audits to reduce operating costs.

**District DOT:** DDOT is changing fans from chain drive to belt drive to reduce operating costs. It is also looking at ways to reduce the amount of over-height damage. Over-height vehicles can now be identified. It is now focusing on prohibiting or at least discouraging the operators and owners of these vehicles from using the tunnels.

**MassDOT:** MassDOT is moving toward risk-based and condition based inspection to be more cost effective. It has aggregated procurement of tunnel electricity to lower costs and is shifting from unskilled personnel to skilled personnel, including maintenance, to handle more work in-house.

**PennDOT:** PennDOT is upgrading M&E components during rehabs to reduce operating costs (e.g., monthly utility bills). The PTC is also optimizing lighting and ventilation equipment and operation time (e.g., through variable speeds and operational levels).

**PANY&NJ:** At the Lincoln Tunnel, the PANY&NJ is looking toward reducing utility consumption and costs, reducing and eliminating the scope of some contracts, reducing non-critical maintenance activities, and reducing labor costs by reducing nonemergency overtime. At the Holland Tunnel the PANY&NJ has started a program to replace much of its lighting with more energy-efficient sources, including LED lighting and motion sensors to ensure that most of the lighting within its buildings is off when staff is not in the area.

**VA CBBT:** The CBBT District takes a proactive stance on maintenance, with bond resolution documents requiring it to maintain an overall rating of seven out of nine for the facility.

**VDOT:** VDOT has no measures or program currently in place.

**WSDOT:** WSDOT is moving its tunnel operators to its central facility, doing more work in-house, purchasing systems and equipment that can be maintained in-house, stockpiling parts from obsolete equipment, and reducing power usage by turning off lights and fans when required.

#### *2.2.5.3 Trials of Emergency Response Systems*

Tunnel owners that the scan team visited conduct and document periodic trials of their emergency response systems (e.g., fire suppression, fire identification, communication, and ventilation). Examples include:

- Written hourly records of all tunnel devices, such as ventilation systems
- Periodic trials of fire suppression systems with local responders; written trial reports filed
- Monthly tests of automated control systems for fire alarms and ventilation systems
- Monthly and annual trials of ventilation systems and backup generator systems
- Quarterly tests of safety systems with public safety and fire department personnel
- Quarterly operational tests of integrated systems for fire detection, ventilation control, and lane control signals
- Semiannual or annual tabletop exercises with surrounding communities, local emergency responders, and state and local police
- Annual live fire training at local fire stations; monthly drills and tests

- Annual fire response field tunnel exercises involving the live burn of a mock vehicle with facility and municipal fire department response
- Walkthroughs with fire departments and Emergency Medical Services personnel

Records are kept in databases, such as maintenance management systems.

**AKDOT&PF:** The AKDOT&PF tests its entire safety system quarterly. Both Whittier Public Safety and the Anchorage Fire Department have participated; the results are available. In addition, the AKDOT&PF conducts random tests.

**Caltrans:** Caltrans has a documented emergency response plan for the newest tunnel projects in design and currently in construction. Inspection reports recommend that fire protection standpipe systems be tested by the local fire agency, and these inspection tests are occurring at five year intervals. CO monitoring equipment is recommended for calibration and servicing. Ventilation fans are not tested for performance; however, each year Caltrans measures and documents megohmmeter testing of winding insulation, power consumption, high and low speed fan operation, and SCADA remote operation. Individual inspection reports are available for the specific tunnels.

**Colorado DOT:** At the EJMT, a few tabletop exercises are conducted with surrounding communities, local emergency responders, and state and local police approximately once a year; some records are available. The entire fire ventilation system is not tested regularly due to the excessive cost to operate it; however, individual fans are tested. The fire truck and gear are inspected every 8-hour shift, the pumper is tested weekly, and fire responders are trained once annually and drilled sporadically by supervisors.

The HLT does live fire training once a year at local fire stations, monthly drills, and monthly tests from the current International Fire Service Training Association manual. Fire apparatus are inspected every shift, along with bunker gear and self contained breathing apparatus. Ventilation fans have been tested in the past with “cold” smoke to evaluate their efficiency. Supervisors periodically conduct a pumper drill with a scenario that the responding crew has to handle.

**District DOT:** Extensive testing of an integrated system has just been completed as part of the rehabilitation of fire-detection and ventilation control systems and the installation of lane control signals. Operational tests of the integrated systems are scheduled quarterly.

**MassDOT:** Every six months, during the second and fourth quarters, MassDOT runs the ventilation fans at full capacity (emergency level) for 15 minutes in accordance with its Tunnel Inspection and Testing Program and local fire codes. It cleans the plenums before each test and runs the tests after tunnel washing and during rainy days to avoid dust being dispersed into the air. It runs 85 mph wind in the plenums at maximum velocity, with three minutes from minimum to maximum velocity. The tests of the fire zones are run in three modes: automatic, manual, and from the ventilation building. Tests are documented. All fire extinguishers are checked monthly.

MassDOT’s HOC is the point of contact for coordination. It coordinates with the various departments before, during, and after testing to develop the schedule, conduct the test, and follow up with any equipment alarms and failure issues. Coordination includes:

- Access work – ensures that no activity takes place inside the plenums during testing
- Community outreach – for public outreach, for example, when a ventilation building is close to residential neighborhoods
- Operations – HOC operators perform the testing
- Communications – monitors fan performance during testing
- Electricians – perform part of the test and reset the fans as needed
- Environmental – performs continuous emissions monitoring
- Maintenance engineering – addresses follow up issues

MassDOT prepares a quarterly life-safety report that documents whether the life-safety preventive maintenance requirements were met. The report is filed, not published.

MassDOT believes that a minimum level of regular testing (e.g., every six months) should be required for M&E systems to ensure that the ventilation will work at full emergency mode in case of a fire. The test requirements should include operating procedures for the owner's personnel.

**PennDOT:** PennDOT does a walkthrough with the City of Pittsburgh Fire Department and Emergency Medical Services personnel. The first of every month it tests the automated control system for fire alarms and ventilation systems. The PTC conducts annual training sessions with the "Authorized Services" that respond to calls on the system.

**PANY&NJ:** The Holland Tunnel has at least two drills each year. One is a tabletop drill and involves outside agencies, and one is a mutual aid drill that also involves outside agency participation. The Lincoln Tunnel conducts an annual fire response field tunnel exercise involving the live burn of a mock vehicle, response by facility and municipal fire departments, exercise of tunnel fire protection and ventilation systems, and use of communications and incident command activities.

**VA CBBT:** Communications are tested daily. Fire suppression, Purple-K on the Mack trucks, is tested twice a year. Operators on the islands keep hourly records of all tunnel devices, such as the ventilation system; this is the only one with a written record.

**VDOT:** VDOT has periodic trials of its fire suppression (deluge system) and its communication (CCTV and pull stations). Frequencies are as required by NFPA. Local responders participate, and reports are prepared for each trial and kept on file.

**WSDOT:** WSDOT has yearly trials of the fire system monthly and annual trials of the ventilation system, and monthly and annual trials of the backup generator system. The fire department gets the results of the fire system tests. The other systems are captured from the maintenance management system. Reports are available; however, they are essentially work order reports.

### *2.2.5.4 Procedure to Keep Records of Fire Incidents*

Tunnel owners have procedures in place to keep records of fire incidents in their tunnels. Some owners record all incidents in computerized maintenance management systems. Others have incident reports for unusual conditions, handwritten and electronic shift operating logs and incident logs that track fire and other incidents, digital video recordings of all incidents, and fire incident logs and fire-system event recorders. Fire departments keep local and national tunnel fire records via the National Fire Incident Reporting System. These data are available to U.S. tunnel owners.

**AKDOT&PF:** All incidents are recorded.

**Caltrans:** Caltrans has incident reports for unusual conditions and a 24/7 logging recorder.

**Colorado DOT:** The HLT maintains both a shift log and an incident log to track fire incidents as well as all other incidents. These records are both handwritten and electronic.

**District DOT:** Incidents requiring a maintenance response are recorded in the computerized maintenance management system.

**MassDOT:** MassDOT maintains digital video recordings of all incidents. An after actions meeting attended by all parties involved occurs for all major incidents to communicate and coordinate any possible improvements to response.

**PennDOT:** At the PTC, all reportable incidents are documented and logged through its Central Command.

**PANY&NJ:** The Holland Tunnel has fire-related reports (forms) that are submitted for every incident; the Risk Management Division keeps copies of these reports. Lincoln Tunnel fire incidents are tracked via operating logs; tunnel management and supervisory staff maintain the incident reports.

**VA CBBT:** Operators on the islands keep an hourly record of many aspects of occurrences in and around the tunnel.

**VDOT:** Control room personnel log all fire incidents.

**WSDOT:** WSDOT keeps records of fire events on the tunnel log and fire system event recorder; the new system has a log.

### *2.2.5.5 Mechanisms Deployed for Fire Safety and Minimized Damage*

The tunnel owners have deployed various mechanisms to ensure that a fire in the tunnel can be contained to levels that do not pose hazards to the tunnel structures or operating systems and that limit the public's exposure to excessive heat, smoke, and CO levels. These mechanisms include:

- Emergency response plans and trained emergency response teams
- Fire-detection and surveillance systems, including heat and smoke monitoring

- Fire suppression-systems
- Computerized smoke ventilation systems activated and monitored by 24/7 tunnel systems controllers
- Co-monitoring
- Manual pull stations with dedicated phones
- Emergency safe-houses
- CCTV monitoring
- Traffic control systems
- Fire standpipe systems
- VMSs and highway advisory radios (HARs) with flashing red strobe lights to identify emergency exits

See Figure 2.34 for an example of tunnel fire safety equipment.

**Figure 2.3** ***Fire safety equipment in a highway tunnel in 2009***

**AKDOT&PF:** Heat, smoke and CO are monitored. A fire can be contained using the doors, fans, and fire-suppressant resources. In addition, the public can escape to safe-houses.

**Caltrans:** Existing major tunnels have ventilation equipment, CO monitoring, CCTV monitoring, traffic control activated by maintenance crews, full fire-protection standpipes with fire department connection in the structure, and manual pull stations with a dedicated phone to the OMC operators. The Doyle Drive Southbound Battery Tunnel will also have deluge-sprinklers. Existing minor tunnels have CO monitoring, CCTV monitoring, traffic control activated by maintenance crews, and full fire-protection standpipes with fire department connection in the structure.

**Colorado DOT:** An EJMT fire ventilation study was performed in 2001. The EJMT follows the study's recommendations and has equipped its fan control board with failsafe light indicators to ensure correct system operation for each tunnel segment and eliminate operator error under stress.

The HLT trains its staff to respond to and extinguish a car fire in six minutes or less. All traffic in both directions is stopped outside the portals, and any traveling public stopped in the tunnels are instructed to evacuate the bore on foot through cross-passages to the other bore. This is accomplished by electronic message boards and HAR messages, along with flashing red strobe lights to identify the emergency exits.

**District DOT:** Heat detectors, lane control signals, and VMSs are operational and tested for operational optimization. Preventive maintenance plans for safety critical systems (i.e., fire, ventilation, and CO) are designed to provide assurance that the systems operate reliably. Tunnel operators are trained to ensure that they know how to operate the ventilation system, lane control signals, and VMSs manually if system degradation prevents automatic operation.

**MassDOT:** The purpose of MassDOT's ventilation response plan is to draw air and smoke away from traffic. Zones behind the incident provide fresh air. At maximum capacity, all air is changed in three minutes. A maximum of 10 ppm CO is allowed. MassDOT has its own tow trucks and incident response stations. The Massachusetts Department of Environmental Protection (DEP) has requirements for air quality and clearing incidents (response time). The Boston Fire Department's response time is three to five minutes.

All firefighters receive the same training and have additional equipment (e.g., 30 gallons of foam with the nozzle in the front). All first responders receive annual training through drills to ensure coordination; the drills are conducted without fire.

**PennDOT:** When CO levels in a tunnel reach 100 ppm, PennDOT immediately closes the tunnel, calls 911, and removes all vehicles from the tunnel; tunnel vents then take over. The PTC utilizes early detection and monitoring for heat, CO, and physical obstructions, coupled with 24/7 staffing and standard operations.

**PANY&NJ:** The Lincoln Tunnel utilizes ITS and a robust CCTV system to detect incidents. The tunnel has a fire standpipe system and a computerized tunnel smoke ventilation system activated and monitored by a 24/7 tunnel systems controller. The facility has its own 24/7 fire response complement with emergency response equipment that contains a light water and Purple-K foam system. The Lincoln Tunnel also has emergency personnel stationed inside the tubes during peak traffic times.

Both the Holland and Lincoln Tunnels have a fully transverse ventilation system. Operation of the emergency smoke exhaust ventilation system is validated by use of computational fluid dynamics modeling to confirm that a tenable condition is maintained outside of the fire zone, to provide both safe egress for passengers and a means for first responders to access the fire zone.

**VA CBBT:** The CBBT District has a limited fire suppression system located on Mack tow trucks on the islands. For large events, however, it has nearby fire and rescue stations at either end of its facility: Cape Charles Fire and Rescue to the north and Chick's Beach Fire and Rescue to the south. To limit exposure to smoke and CO, the ventilation system has the capability to replace every cubic inch of air in the tunnel in two minutes when all fans are turned to the highest setting.

**VDOT:** VDOT uses the transverse ventilation system.

**WSDOT:** Fire-detection and surveillance systems and fire suppression and ventilation systems are incorporated into WSDOT's long tunnels.

#### 2.2.5.6 Procedure for Communicating with Local Emergency Services

Tunnel owners have worked with local fire, police, and emergency medical services to establish protocols for communicating during a tunnel emergency, but most do not have interoperable communication systems with first responders and life-safety agencies during tunnel incidents. Traffic incident management plans have been established to make use of National Incident Management System protocols.

Most tunnel operators coordinate with emergency services using telephones and radios. Some tunnel owners share their frequencies with local police and fire agencies. Some tunnel computer systems are integrated with the fire department, and operators communicate on fire department radio channels. In some cases, during an incident local agencies respond to an incident by reporting to a designated staging area, where they are issued facility radios for communications that are coordinated through the operations center. Interoperable systems include 800-MHz digital radio, 144 MHz conventional very high frequency (VHF; 30 to 300 MHz) radio, and individual cell phones where coverage is available. Conventional radio VHF broadcasts and digital two-way radio call groups are also used.

**AKDOT&PF:** The Whittier Tunnel fire brigade is the first response team. The tunnel operator coordinates with outside agencies as needed for support services.

**Caltrans:** Caltrans mainly use telephones. Emergency services use White Net (Office of Emergency Services White Channels - radio), which Caltrans can also utilize.

**Colorado DOT:** EJMT communication procedures vary depending upon the Interstate or highway incident impact level, geographic location, and incident/event duration. The DOT uses multiple systems to communicate from the communication center to other centers, as well as from EJMT dispatch directly to first responders and adjoining "life-safety" agencies. Interoperable systems include 800-MHz digital radio, 144 MHz conventional VHF radio, and individual cell phones, all as appropriate where coverage is available. Conventional radio VHF broadcasts and digital two-way radio call groups are used extensively to ensure uniform information is dispersed expeditiously.

The HLT has shared its local frequencies with local law and fire agencies. At any given time it can communicate with responding agencies via its 800-MHz and VHF radios. It has worked with the Colorado State Patrol and fire agencies that respond into Glenwood Canyon to establish communication protocols. Traffic incident management plans have been established to make use of National Incident Management System protocols for large scale/ongoing incidents and protocols listed by EJMT. This alleviates the impact to the traveling public and better manages traffic so that cities and towns are not adversely affected by the influx of traffic.

**District DOT:** The contractor contacts the police department, fire department, emergency management unit, and the emergency management center.

**MassDOT:** MassDOT's HOC computer system is integrated with the Boston Fire Department (BFD), which responds to all fires in the tunnels. The BFD gets the fire location, route, and counter flow route from the HOC, which can talk with the BFD on its own radio channel, saving response time. If the BFD cannot access the fire location the regular way, the state police will escort them counter flow from an exit upstream of the fire. HOC command staff and operators go over the tunnel ventilation systems' operations and settings with the BFD so that its personnel are comfortable with them. During a major event, the Boston Fire Chief (incident commander) goes to a specific station at the HOC to assist in coordinating with the BFD.

**PennDOT:** PennDOT makes phone calls to the appropriate personnel. The command center dispatches and communicates with all PTC personnel, police, fire, and Emergency Medical Services via radio network.

**PANY&NJ:** During Holland Tunnel emergency incidents where mutual aid assistance is required, the PANY&NJ will contact the local agencies within 10 minutes of when the incident occurs. These agencies will respond to the facility to pre designated standby positions. Once at those locations, they will be issued facility radios, and the PANY&NJ Communications Desk with coordinate their responses. Their agency-issued radios do not have interoperable communication ability.

For the Lincoln Tunnel, the outside municipal agencies respond to designated staging areas, where they pick up facility radios. Initial communications are made via direct telephone link and 911 systems.

**VA CBBT:** The CBBT District has its own police force. Its police officers have in car capabilities to communicate with Cape Charles Fire and Rescue to the north of the facility. To the south, communication with Chick's Beach Fire and Rescue is accomplished through a radio system at the District's South Plaza Station by the Plaza Supervisor, who relays information from South Plaza between the scene and the responders.

**VDOT:** Participants in VDOT's Strategically Targeted Affordable Roadway Solutions (STARS) system (a safety and congestion program) and fire responders act as incident commanders in the Hampton Roads District. The Bristol district uses 911 and calls in to the Salem Tunnel Operations Center.

**WSDOT:** WSDOT's Traffic Management Center/Transportation Control Center (TMC/TCC) has a telephone connection to the local emergency dispatch center, as well as an intercom connection with the state police. WSDOT has radio links in the existing tunnels to the fire department and the police. It currently does not have an interoperable radio system with emergency responders; however, a system is in the works that may have this capability.

#### *2.2.5.7 Systems and Protocols for Emergency Information to Public*

The tunnel owners use various systems and protocols to provide information to the public regarding emergency conditions in the tunnel and the forms of egress to use should an evacuation be necessary. These include VMSs on the approaches, highway advisory AM radio, AM/FM radio rebroadcast for motorists within the tunnel, traffic signals inside and outside the tunnel, and press releases to the media. During an incident, all traffic is stopped outside the portals, with any motorists stopped in the tunnels instructed to evacuate on foot through cross-passages. In some tunnels, flashing red strobe lights identify emergency exits, and some tunnel owners are considering the use of audible alarm systems. Tunnel Web sites are updated as information and time allow.

**AKDOT&PF:** AKDOT&PF uses changeable message boards, AM radios, and phones as its primary means of providing emergency information to the public. It augments these by updates to the Web site as information and time allow.

**Caltrans:** Caltrans mainly uses telephones. Emergency Services uses White Net (radio), which Caltrans can also utilize.

**Colorado DOT:** The EJMT uses strobe lights at the cross-passages. The HLT uses electronic message boards and HARs, along with flashing red strobe lights to identify the emergency exits. All traffic in both directions of the HLT is stopped outside the portals, and any traveling public stopped in the tunnels are instructed to evacuate the bore on foot through cross-passages to the other bore.

**District DOT:** DDOT notifies the public; DDOT is in contact with police and the fire department. During an emergency, shoulder space is used for evacuation.

**MassDOT:** The HOC has a procedure to notify the media, responders, and others in the event of an emergency. Sister agencies are notified of incidents. Signs tell motorists to stop and not to enter the tunnel. MassDOT experience has been that motorists do not stop when the VMSs direct them to stop. In fact, with small fires, motorists will go around the fire in the lane that is open.

**PennDOT:** PennDOT issues press releases to the media, which have personnel working in PennDOT's TMC. ITS cameras monitor accidents 24/7 and can be viewed by staff in the TMC and by tunnel personnel. The PTC uses HAR and VMS networks to advise the traveling public of real-time incidents.

**PANY&NJ:** The PANY&NJ tunnels utilize VMSs on the approaches, as well as in tunnel radio, to alert motorists. Additionally, the PANY&NJ can dispatch bridge and tunnel alerts to subscribers via text, e-mail, or cell phone message.

**VA CBBT:** CBBT traffic is stopped at both the north and south toll plazas.

**VDOT:** VDOT public affairs personnel and AM radio station messages notify local travelers of a tunnel incident. The AM/FM rebroadcast system is used to address motorists in the tunnel; 511, a one-stop resource for information such as real-time traffic conditions, route planning, and travel mode alternatives, is used.

**WSDOT:** For its existing long tunnels, WSDOT uses radio rebroadcast, strobes, traffic signals, and tunnel closure signs. For the proposed SR 99 tunnel, WSDOT is working with the Seattle Fire Department to determine how best to address this issue. In addition to the items in its existing tunnels, WSDOT is considering using a public address system, full matrix full color signs, and an audible alarm system.

## 2.2.6 General

### *2.2.6.1 Recommended Changes for the 2010 AASHTO* Technical Manual for Design and Construction of Road Tunnels – Civil Elements

This manual ballot item was voted on and passed at the AASHTO SCOBS annual meeting in early July 2009. The manual was published as an AASHTO publication in August 2010 (see Figure 2.4).

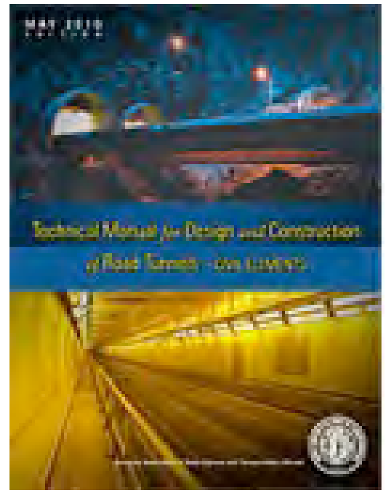


**Figure 2.4** ***2010 AASHTO Technical Manual for Design and Construction of Road Tunnels – Civil Elements***

After reviewing the manual, tunnel owners felt that additional information should be included on M&E systems design, fire and life-safety issues, and guidance such as for shoulders and emergency egress.

**Caltrans:** To be called a definitive manual on tunnel design, Caltrans believes that this manual should include more information on the M&E and fire/life-safety topics. The M&E discussions that were included do not give enough weight to the interaction M&E design has with the civil topics. The design requirements for M&E systems often drive the structure criteria and envelope.

**WSDOT:** WSDOT would find it helpful if the section on highway shoulders set desirable standards for highway tunnels. In addition, the manual needs additional discussion on emergency egress. If ADA standards are not required, the section on the emergency egress should set a standard for designers to meet (e.g., rescue or refuge areas will be provided every X feet).

### 2.2.6.2 Use of a Tunnel Management System to Track Condition, Inspection, Repair, and Needed Funds

In 2005, the FHWA and FTA jointly developed and published a TMS comprising two manuals and a software program. *The Highway and Rail Transit Tunnel Inspection Manual*[27] provides guidance on:

- Tunnel construction and systems (e.g., tunnel types, ventilation systems, and lighting systems)
- Fundamentals of tunnel inspection (i.e., inspector qualifications and responsibilities, equipment/tools, mobilization, methods of access, and safety practices)
- Inspection procedures for structural elements and mechanical/electrical systems
- Definition of condition codes (0 to 9, similar to bridge inspection codes)
- Inspection documentation

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[27] *Highway and Rail Transit Tunnel Inspection Manual*, FHWA, U.S. Department of Transportation, Publication No. FHWA IF 05 002, 2005

- Repair priority definitions
- Report format

The *Highway and Rail Transit Maintenance and Rehabilitation Manual*[28] provides guidance on:

- Tunnel construction and systems (e.g., tunnel types, ventilation systems, and lighting systems)
- Preventive maintenance recommendations for various tunnel elements and systems
- Rehabilitation guidelines for structural elements for water infiltration, concrete repairs, and liner repairs
- An appendix on life-cycle cost methodology

The software that goes with the manuals is used to collect and manage tunnel component data. The TMS is available to all U.S. highway and transit tunnel owners and operators. Agencies currently using the FHWA/FTA TMS are DDOT, PennDOT, the PTC, and the North Texas Tollway Authority.

DDOT piloted the FHWA/FTA TMS in 2003 and is using the TMS to track condition, inspection, repair, and needed funds for all its tunnels. PennDOT is using the TMS to collect condition information for three of its tunnels. Alaska, Colorado, Massachusetts, and Washington State each use their maintenance management system for their tunnels, and the PANY&NJ is developing its own centralized asset management system. Other tunnel owners do not use a TMS.

**AKDOT&PF:** AKDOT&PF does not use a TMS but does have a maintenance management system in place.

**Caltrans:** Caltrans has determined that the relatively small number of tunnels in the state does not warrant the overhead required for an independent TMS.

**Colorado DOT:** The HLT has been using a maintenance management system since the tunnel opened in 1992.

**District DOT:** DDOT was the first tunnel owner agency to pilot the FHWA/FTA TMS to collect and manage data on its highway tunnels[29]. In fall 2003, DDOT piloted the TMS for inspection of its 17 highway tunnels, using it to collect and manage the data. In fall 2005, it hosted a workshop that highlighted this implementation. DDOT now uses the TMS for all inspections.

**MassDOT:** MassDOT requires a more detailed TMS than that provided by the FHWA TMS. MassDOT's *Tunnel Inspection and Testing Program Policy Directive* provides a uniform policy for tunnel inspection. In accordance with the directive, condition evaluation of the tunnel elements must be consistent with the MassDOT November 2003 *Inspection Manual for Tunnels and Boat Structures, Volume 5*; the FHWA 2005 *Highway and Rail Transit Tunnel Inspection Manual*; and the various MassDOT HOC response plan documents.

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[28] "Showcasing the DC Tunnel Management System," *Focus,* FHWA, U.S. Department of Transportation, October 2005

MassDOT has its own MMIS to schedule, track, and document maintenance. The MMIS is mainly focused on M&E systems to date. The facilities and associated equipment that MMIS is tracking include tunnel ventilation buildings, maintenance facilities, electrical substations, storm water and low point pump stations, state police and emergency response stations, and administration buildings. MassDOT's tunnel inspection policy now requires that MMIS reports be run.

**PennDOT:** PennDOT is implementing the FHWA/FTA TMS for inspection of three tunnels as a way to collect condition information. It uses the *Highway and Rail Transit Tunnel Inspection Manual* as a guide for condition rating, but is limited because it does not mandate any specific or consistent time between inspections, any specific training for inspectors, or the use of standard reporting forms for the inspection or inspection results.

has used the TMS software program to store tunnel inspection results and assist in the development of rehabilitation plans. The software is designed to allow tunnel owners to monitor the physical condition of their tunnel assets over time to identify trends in performance and maintenance. It provides various data using a graphical point and click interface that simplifies navigating through large amounts of data. The software facilitates a comprehensive inspection documentation/recordkeeping system, with most inspection information (e.g., report data, typical condition reports, and photos) appearing in the system. It does, however, require foresight in data collection methodology and file organization. PennDOT has compiled owner and end user suggestions for enhancing the integration of differing codes, ratings systems, and methodologies.

The PTC is re-establishing itself in the FHWA/FTA TMS after its old system became technologically obsolete.

**PANY&NJ:** The PANY&NJ is developing its own centralized asset management system. Its goal is to track conditions and related structural information (e.g., original contract drawings, shop drawings, repairs, and costs of inspections and repairs). It also has developed its own guidelines for tunnel condition surveys, which has resulted in good consistency in inspection codings and conditions between in-house and consultant inspectors.

**VA CBBT:** The CBBT District does not use a TMS.

**VDOT:** VDOT does not currently use a TMS, but is looking into the possibility of obtaining or developing one.

**WSDOT:** WSDOT does not use a TMS; instead, it uses a maintenance management system as a tool to help manage tunnel and tunnel systems maintenance.

### *2.2.6.3 Recommended Additional Standards, Guidance, and Best Practices*

Tunnel owner hosts recommended reviewing other international standards and using the same staff for both inspections and rehabilitation drawings. They also recommended specific documents and details as described below.

**Caltrans:** Caltrans recommends incorporating the National Pollutant Discharge Elimination System, Storm Water Quality Handbook, Maintenance Staff Guide, and Caltrans Maintenance

Manuals 1 and 2. Its SM&I feels strongly that a new TMS should not be mandated; instead, the needs of a TMS should be incorporated into other systems, such as the BMS and Integrated Maintenance Management System.

**District DOT:** DDOT has found that it is best, when possible, to use the same knowledgeable staff to perform the inspections and rehabilitation drawings, as they are familiar with the tunnel.

**MassDOT:** MassDOT recommends that a review of other international standards be conducted. Many countries have far more extensive or mature roadway tunnel systems and codes, notably Switzerland (ASTRA), Japan (1500 roadway tunnels), and Germany (DIN).

**PANY&NJ:** The PANY&NJ takes settlement surveys and soundings. It requires that the cables and wires (further called "cables") installed in its tunnels comply with the following requirements:

- Polyvinyl chloride insulated cables shall not be installed in its tunnels, except for communication systems, signaling, and power limited-circuits.
- Cables must have a thermoset, low smoke, zero halogen, cross linked polyolefin insulation..
- Cables shall pass the flame propagatory test VW-1 and be Underwriters Laboratories listed as XHHW-2 rated 90 degrees for both wet and dry applications.

Cell phone antennas and an 800-MHz police system are also in the tunnels.

## 2.3 Specialized Technologies Currently Used for Existing and New Roadway Tunnels

Owners were asked about specialized technologies they currently use for their existing and new tunnels. Their responses are provided below in the categories of design; construction; maintenance, repair, and rehabilitation; inspection; and operations. A general category is also included.

### 2.3.1 Design

#### *2.3.1.1 Lighting Luminance*

Specialized technologies for tunnel lighting luminance include proprietary systems to control light intensity levels and dimming versus switching technology. A number of tunnel owners are considering LED lighting for increased energy efficiency and reduced maintenance requirements.

**Caltrans:** Caltrans works with light fixture vendors to model the tunnel surface light intensity for light spacing and fixture wattage. This standard is based on the ANSI/IESNA Recommended Practice for Tunnel Lighting, RP-22-2005, which specifies HPS tunnel lighting fixtures and group lights for three lighting levels (i.e., night/emergency, direct bright sunlight, and cloud conditions) in the tunnel's transition zones. An analog photocell (or photo diode, luminance sensor) measures the ambient light on the roadway before the tunnel and sends a signal to the PLC that controls the tunnel lights' operation. Depending upon the PLC's programming, groups of lights will turn on and off at preset ambient lighting levels to maintain an adequate lighting level inside the tunnel for different exterior lighting levels (i.e., day, night, cloudy, or foggy).

**Colorado DOT:** The EJMT utilizes a lighting control system based upon four photometers, one facing away from the tunnel portal faces and another at each portal. Comparison of the metered light levels determines appropriate illumination at the portal entrance and outbound locations, which is critically important for transitional or “high intensity zones.”

The HLT uses a two photometer system that only monitors the inbound light intensity. Each entrance utilizes LPS and fluorescent lighting for transitional lighting. It is currently investigating updating the lighting system with more energy-efficient systems. The RCT uses one photometer and operates essentially the same as the HLT.

**MassDOT:** MassDOT has not used specialized technology for tunnel lighting luminance. It is considering using electronic fluorescent ballast in place of electromagnetic ballast and is evaluating application of LED lighting.

**PennDOT:** PennDOT uses HPS lights and is considering experimenting with LED lights. The PTC has employed different methods of lighting design and fixture type, from the original linear fluorescent to HPS and metal halide systems.

**PANY&NJ:** The PANY&NJ is considering replacing existing tunnel lighting (linear fluorescent and HPS) with an LED lighting system that has dimming capability so that the lights can be brought back up to brightness since LED lights may lose some brightness over time. In addition, the color can be a little too blue for some applications. The anticipated benefits are longer life and watertight lights during tunnel washing. PANY&NJ currently has pilot projects (e.g., to evaluate electricity reduction, performance, and maintainability).

**VA CBBT:** The CBBT District uses a proprietary lighting control system. Each of its two tunnels has a lighting controller to provide a level of intensity during daylight hours. A sensor outside each tunnel entrance in the portal area sends a signal to the controller; the controllers are interfaced with each other. The system adjusts to five levels of intensity, with level 1 being the nighttime setting. The overall goal is to eliminate the “tunnel effect,” which can cause a moment of temporary vision degradation when motorists drive into the portal area.

As a test, four miles from the tunnel, the CBBT District has installed 10 LED lights provided by suppliers. It is also in the process of installing LED on its fishing pier. LED for roadway lighting, however, has not proven itself in the CBBT District environment at this time.

**VDOT:** VDOT considered LED lighting, but it was cost prohibitive.

**WSDOT:** WSDOT has considered using LED fixtures on proposed and current tunnels to reduce tunnel power requirements. However, it has not found lighting fixtures that can provide the required lighting levels. It attempted an experiment to replace HPS fixtures with LED fixtures for a section of one of its I-90 tunnels, but the existing housing was not suitable for LED fixtures. Currently it uses proprietary lighting software for lighting analysis. For the Alaskan Way Viaduct tunnel currently under design, it will investigate dimming versus switching lighting technology, although it has had not found this technology to be beneficial in the past.

#### *2.3.1.2 Air Quality and Opacity Air Quality Requirements*

Ventilation systems, CO/nitrogen oxides (NOx)/particulate matter (PM) monitoring systems, and fire and life-safety provisions are utilized in tunnels as needed based on design calculations of anticipated air quality exposure levels and EPA/OSHA requirements. The extent of ventilation capacity is based on tunnel length as defined by NFPA 502. Regulation varies from internal handling to reporting to local or state environmental agencies. Video is used to monitor opacity; ventilation stacks do not typically have air scrubbers.

**AKDOT&PF:** The Anton Anderson Memorial (Whittier) Tunnel is one of the first tunnels in the U.S. to use jet fans for ventilation. The AKDOT&PF monitors its CO levels due to the mix of trains and vehicles, but has no specific regulator.

**Caltrans:** Caltrans does not specify specialized air quality equipment (e.g., video imaging, laser based imaging, or newer technologies). Instead, it specifies local CO and NOx monitors located in the tunnel and dedicated to a zone. The monitors are manually calibrated, and sensors are replaced by a maintenance schedule.

Design calculations for all tunnels, including short tunnels that normally would not be expected to require ventilation, must show that CO exposure levels will not exceed the EPA maximum exposure levels during normal ADT volumes and the predicted maximum vehicle per hour traffic rate. If design calculations (i.e., computer modeling) of CO exposure levels show they could reach 50 ppm for the expected exposure time of vehicles in the tunnel, then real-time CO monitoring equipment must be installed and monitored and the contract drawings must provide for future addition of ventilation equipment. This means that sections in the structure must be blocked out for ducting and mounting of ventilation equipment, and empty power conduits to the future equipment locations must be provided. If design calculations of CO exposure levels show they could reach 120 ppm for the expected exposure time of vehicles in the tunnel, then the contract drawings must provide for the installation and operation of ventilation equipment, electrical power and controls, CO monitoring equipment, and fire/life-safety provisions.

The extent of ventilation capacity is based on the tunnel length as defined in the latest edition of NFPA 502 and as follows:

- For tunnels less than 300 feet in length, specific ventilation and fire/life-safety provisions are evaluated on a case-by-case basis, with engineering analysis required for evaluation.
- For tunnels 300 feet and greater in length, if engineering analysis indicates CO accumulations are probable, at a minimum ventilation capacity is required to dilute CO concentrations. Two-speed fans will operate at low speed when concentrations reach 60 ppm CO and high speed when concentrations reach 100 ppm CO. All other provisions of NFPA 502 apply.
- For tunnels lengths greater than 800 feet, all provisions of NFPA 502 apply, and ventilation

capacity must produce the critical velocity required to prevent back layering of the smoke of a design fire.

Documentation of air quality sampling is expected to be recorded and stored for historical and tort liability. Ventilation stacks (usually exhaust) do not have air scrubbers.

**Colorado DOT:** The EJMT effectively employs the original full transverse ventilation system. The HLT has not needed to run fans routinely, as the normal CO levels remain below 15 ppm.

Historically, the requirement has been a maximum 100 ppm for CO. CO ppm measurements are taken in the exhaust plenum immediately prior to being exhausted into open air. Much lower levels (i.e., 5 to 20 ppm) are typical.

The Colorado Department of Health and Environment is the regulating agency, but there is limited scrutiny due to decades without violations. CDOT does not have air scrubbers on its ventilation stacks.

**MassDOT:** MassDOT is under Massachusetts DEP air quality requirements. It follows the DEP regulated Continuous Emissions Monitoring (CEM) Program, which is unique to Boston. The CEM is a hybrid of ambient air quality monitoring and continuous emissions monitoring systems. Emissions are regulated as a direct source, similar to power plants, although vehicular exhaust is an indirect source, and monitored over time for air quality concentration with respect to time. CO and PM-10[30] are measured continuously, while NOx is calculated using a CO:NOx correlation. Emission limits are as follows:

- Maximum CO is 70 ppm in one hour
- Maximum NOx is 8.88 ppm in one hour
- Maximum PM-10 is 500 mg/m$^3$ in 24 hours

New state regulations on PM go from PM-10 to PM-3. The hourly average is reported at 16 locations in ventilation buildings, exhaust plenums, and entrance and exit ramps. Typical equipment components at each location are continuous CO gas analyzer, multi gas calibration unit, zero air generator, data logger, CO calibration gas, and a PM-10 sampler at four locations. CEM design and capital cost were $2 million, with annual non labor operating costs of $200,000, including a five year permit renewal. The CEM labor requirements to operate, maintain, and report are two environmental technicians and one senior environmental engineer. The CEM is independent of in tunnel CO monitoring.

**PennDOT:** PennDOT has done CO monitoring inside tunnels only. Air sampling is continuous, but there are no reporting requirements. PennDOT does not have air scrubbers on its ventilation stacks.

**PANY&NJ:** The PANY&NJ follows OSHA and EPA regulations and monitors CO levels

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30 PM standard that includes particles with a diameter of 10 micrometers or less

accordingly. The PANY&NJ is self regulated and does not report to external agencies. Its tunnels are equipped with CO monitors, and CO levels are monitored 24/7 via manned control rooms from which fans are adjusted accordingly. PANY&NJ also monitors NOx. It does not have air scrubbers on its ventilation stacks.

**VA CBBT:** The CBBT District effectively employs the original full transverse ventilation system in its tunnels.

**VDOT:** VDOT uses video monitoring for opacity and CO monitoring for air quality. In accordance with OSHA requirements, the maximum CO level cannot exceed 35 ppm for an 8-hour time weighted average. Air sampling is performed to determine CO levels, and regulation is performed internally by VDOT. VDOT is exempt from discharge regulations based on the Code of Virginia.

**WSDOT:** In normal operation, air is moved through the tunnel portals with a series of jet fans, so specialized technologies cannot be applied. The vertical fans will only operate during extreme congestion or during an emergency. The Puget Sound Air Quality Agency regulates air quality, and the tunnel project must meet local air quality standards, as must all transportation projects. There are regional air quality monitors. WSDOT does not have air scrubbers on its ventilation stacks and will resist installing them since they will only be used occasionally.

#### *2.3.1.3 Waterproofing Systems*

Various waterproofing systems have been used in tunnels, as described below. Tunnels that do not have waterproofing membranes have drainage systems to collect seep water.

**Caltrans:** At the Devil's Slide Tunnel and new Caldecott Tunnel, between the initial lining and the final lining, a geotextile material will be placed against a smoothed shotcrete layer and a waterproofing membrane will be placed against the final lining. This system will drain into an under drain system that will carry the water outside the tunnel and past the portals into a drainage system.

At the Doyle Drive Southbound Battery Tunnel, a geo composite drainage material will be placed at the retaining walls. A waterproofing system will be applied on the inside face of the retaining wall or tunnel walls and will drain into a sub drain system underneath the tunnel and flow out underneath the tunnel.

The Posey/Webster Tubes' precast segments were wrapped in a waterproofing material and timber lagging.

**Colorado DOT:** The Eisenhower bore of the EJMT does not have a waterproofing membrane. The Johnson bore was effectively treated with a membrane. Maintenance forces have drilled past the tunnel liner in the Eisenhower bore in the wet locations of the air ducts and have built a drainage system to collect the seep water in these locations. An extensive drainage system is in place above and below the roadway in both bores.

The HLT includes an elastomeric waterproofing membrane at spot locations with a formation drainage system.

**MassDOT:** MassDOT used specific CA/T project design criteria for corrosion control. In locations where the width allowed, traditional temporary walls were constructed allowing backside waterproofing of the permanent structure. The greatest challenges are posed by embedded conduits collecting and distributing water and at interfaces of various CA/T tunnel construction contracts.

**PennDOT:** PennDOT has used various methods, including grouting, membrane and troughs over joints, and chases and relief holes, with various levels of success. It also uses copper flashing over wall joints.

The North Shore Connector Light Rail Transit cut-and-cover tunnel used 100-mil polyvinyl chloride membrane sheets with fully welded seams.

**PANY&NJ:** Generally at the Holland and Lincoln tunnels, joints at the cast iron or cast steel ring segments are caulked with lead. At cut-and-cover box sections, the invert and sidewalls are waterproofed with brick set in mastic, with exception of the Lincoln Tunnel, which also has brick at the top side. Additionally, all sides of the box section are topped with a multi ply membrane covered with protective concrete. Drainage is handled with sumps.

**VDOT:** VDOT uses a multi layered bituminous application.

**WSDOT:** The AWV Tunnel will use single-pass precast gasketed liner wall panels.

## 2.3.2 Construction

### *2.3.2.1 Tunnel Construction Technologies*

Tunnel owners have used various types of tunnel construction technologies on recent projects, including TBMs and the NATM (SEM), as well as jacked, immersed, drill and blast, cut-and-cover, and build-on-grade-and-cover technologies.

**AKDOT&PF:** AKDOT&PF used drill and shoot on both tunnels.

**Caltrans:** Caltrans used the NATM (SEM) method at the Devil's Slide Tunnel and is using a similar method for the Caldecott Tunnel because of the type of geology, the horseshoe shaped cross section, and the relatively short length of each tunnel. The Posey/Webster Tubes are precast segments that were floated and placed into an excavated trench using the cut-and-cover construction method. The Doyle Drive Southbound Battery Tunnel is cut-and-cover and build-on -grade-and-cover. The 710 Tunnel project is projected to use a TBM.

**Colorado DOT:** The EJMT used a large drill jumbo (i.e., a portable carriage with one or more working platforms equipped with bars, columns, or booms to support several drills); a tunneling shield was used unsuccessfully. The HLT used an innovative technology utilizing drill-and-blast sequenced excavation and rock reinforcement and shotcrete as permanent stabilization.

**MassDOT:** MassDOT constructed various tunnel types in its CA/T Project. The tunnel types included concrete box sections, concrete encased steel frame sections, shield-driven steel tube sections, jacked concrete tube sections, immersed tube sections of both concrete and steel, and steel soldier pile slurry wall sections. The only concrete immersed-tube road tunnel in the U.S. is in Boston.

**PennDOT:** For the North Shore Connector Light Rail Transit bored tunnel, the Port Authority of Allegheny County used a 23-foot diameter slurry pressure balance TBM to bore the dual 2,200-foot tunnels (4,400 linear feet total). The bored tunnel is complete and the project is on schedule and on budget. The machine was manufactured in Germany, shipped to Baltimore in pieces, and then trucked to Pittsburgh, where it was assembled. Ft. Pitt, Squirrel Hill, and Liberty Tunnels and PTC original tubes were all conventional excavation and support. The second Lehigh tube, completed in 1992, was constructed using the NATM after alternative competitive bidding of conventional versus NATM.

**PANY&NJ:** Extensive experience was obtained during the design and construction of the existing Hudson River tunnels, which were completed in the 1920s and 1950s; relevant data are available from historical sources.

Currently the PANY&NJ is participating in design and development studies on the selection of the optimum alignment for the three tunneling segments included in "The Tunnel" Project (i.e., expansion of New Jersey Transit facilities to the new Terminal Station on 34th Street in Manhattan). Design and manufacturing requirements for the TBMs selected for each segment are also being addressed.

**VA CBBT:** Submersible sections were used for construction of the original tunnels, which are now 45 years old and performing well.

**VDOT:** For the underwater tunnels, all construction used the sunken (immersed) tube technology. For the mountain tunnels, the construction used the drill-and-blast technique. TBMs have not been used to date.

**WSDOT:** For the AWV Tunnel, WSDOT is planning to require a TBM for construction of the large diameter bored tunnel (approximate exterior diameter of 56-feet and approximate length of 9,100 linear feet). The design-build contractor will determine whether to use a slurry or earth pressure balance TBM.

#### *2.3.2.2 Accelerated Construction*

Technologies used to accelerate tunnel construction include remote fabrication for rapid onsite installation such as for sunken tubes, rock reinforcement and shotcrete as permanent stabilization, ground freezing and deep-soil mixing for soil stabilization, and a hybrid earth pressure balance machine. Contracting strategies used to accelerate construction include constructability reviews, design-build procurement, cost plus time bidding, incentives/disincentives, and dispute resolution boards among others.

**Caltrans:** Caltrans employs various items in construction contracts to facilitate smooth and early completion of construction contracts. Some of these items include:

- Constructability reviews
- Cost plus time (A+B) bidding
- Incentives/disincentives
- A+B with I/Ds
- Value analysis workshop during the design
- Time-related overhead
- Cost-reduction incentive proposals
- Owner-controlled insurance program
- Elimination of contract retention
- Partnering
- Expansion of subcontracting
- Dispute resolution boards

**Colorado DOT:** The HLT used rock reinforcement and shotcrete as permanent stabilization to accelerate construction. This was first used in the U.S. on the Colorado I-70 Glenwood Canyon tunnels.

**MassDOT:** Ground freezing and deep-soil mixing were used to stabilize the soils ahead of mining operations, allowing for better production versus grouting from the face. In addition, steel immersed tubes were fabricated remotely and then finished and lowered on site. Jacking of large tunnel segments beneath active transportation links was also used.

**PennDOT:** PennDOT has used hydro-demolition on the ceiling at the Liberty Tunnels to remove delaminated concrete. The ceiling was then repaired with latex, dowels, and mesh.

**PANY&NJ:** The PANY&NJ is studying tunneling technologies currently in use worldwide to permit optimum selection of design and construction methodology for inclusion in contract documents. It is considering using a hybrid Earth Pressure Balance Machine for the apparent "mixed face" conditions that it will encounter on the Hudson River Crossing included in "The Tunnel" project.

**VDOT:** VDOT has not constructed a new tunnel for underwater crossings in the last 17 years and more than 35 years for a mountain tunnel. A new tunnel planned in the Hampton Roads area will possibly utilize the sunken tube method.

**WSDOT:** For the AWV Tunnel, WSDOT is planning to require a pressurized-faced TBM and utilize the design-build procurement method to save overall time.

#### *2.3.2.3 Prefabricated Elements*

Prefabricated elements used in tunnels include steel and precast concrete submersed tubes, prefinished manufactured steel ceiling panels, steel wall panels with baked enamel, precast concrete floor, precast concrete ceiling panels with tiles, and precast concrete plenum wall dividers. The only issue related to connections of ceiling panels, and this issue has been resolved. All prefabricated elements are performing well.

**AKDOT&PF:** Precast floor panels were used for the Whittier Tunnel. The panels are performing well.

**Caltrans:** No precast elements are being used for the Devil's Slide or Caldecott Tunnels. At the Posey/Webster Tubes, precast segments were used and are performing well. Caltrans discovered potential issues in the analytical phase at the precast joints during a large seismic event.

**Colorado DOT:** The EJMT used precast plenum wall dividers and ceiling slabs. The system is performing well.

**MassDOT:** MassDOT used prefinished manufactured steel ceiling panels for the Sumner, Callahan, and Ted Williams Tunnels. Precast concrete ceiling panels were used for its I-93 O'Neil Tunnel and I-90 Connector Tunnel for above-roadway exhaust plenums. Wall panels are steel with baked enamel and precast concrete with tiles. The panels are performing well.

**PennDOT:** The North Shore Connector used precast segments with gasketed joints. The segments were high tolerance and used 8,000 psi concrete. The fit-up of the segments and the gaskets had no issues.

**PANY&NJ:** The original cast in place ceilings of the Holland Tunnel (both tubes) were replaced in 1985 with 5 foot × 23-foot precast panels. A smaller portion (approximately 240 feet) of the Lincoln Tunnel ceiling was replaced in 1995. To date these elements have performed well.

**VA CBBT:** The CBBT District's original construction consisted of submersible pieces.

**VDOT:** For underwater tunnels, all VDOT construction used the precast sunken (immersed) tube method.

**WSDOT:** For the AWV Tunnel, WSDOT will require bolted, gasketed, precast concrete liners. The design-build contractor will be allowed to use either cast in place or precast construction for the interior deck structures.

### 2.3.3 Maintenance, Repair, and Rehabilitation

#### *2.3.3.1 Improved Maintenance and Reconstruction Efficiency*

Technologies that improve efficiency in the maintenance and reconstruction of tunnels include:

- Specialized tunnel washing trucks
- Porcelain-coated steel wall panels to improve tunnel washing efficiency
- Higher positioning of lights to avoid truck hits and for easier washing
- Surface mounted light fixtures for easier lamp replacement

- T-8 and T-5 lamps
- LED traffic signals and lighting
- Motion sensor-activated lighting
- Remotely activated pumping systems
- Simplified ceiling support systems
- Panelized wall system alternatives to tile
- Polymer concrete safety-shape barriers
- Variable speed drives in combination with high-efficiency fan motors

Computerized maintenance management system and performance-based contracting are also considered.

**Caltrans:** Maintenance considerations are always present during design of tunnel structures. Caltrans has consistently requested maintenance support to determine its capabilities for maintenance and operation features. Tunnel washing operations drive the wall surface preparation; they have specified porcelain-coated steel wall panels over white paint or simple class 1 concrete finishes. Maintenance personnel request surface-mounted light fixtures for easier lamp replacement. Drainage containment sumps for debris collection and diversion valves in the collection piping have been used to contain tunnel wash water and incident hazardous spills.

**District DOT:** DDOT uses performance-based contracting.

**MassDOT:** MassDOT came up with its own devices to help with maintenance (e.g., specialized trucks). It has also used improved CO detection and PM air quality equipment, remote activated pumping systems, and simplified ceiling support systems.

**PennDOT:** PennDOT has placed lights at higher elevations to prevent them from being hit by trucks and to make them easier to wash. It also upgraded fans, ventilation, and electrical/mechanical equipment at the Ft. Pitt, Liberty, and Squirrel Hill Tunnels. The PTC is experimenting with wall resurfacing and panelized wall system alternatives to tile. Polymer concrete safety-shape barriers have replaced traditional armored curbs.

**PANY&NJ:** The PANY&NJ has recently changed out the 45 watt lights in the Holland Tunnel with LED traffic signals. It is also in the process of changing out the lighting inside each of its four ventilation buildings to lighting activated by motion sensors. LED lighting in its tunnels will have a longer lifespan and improve efficiency by reducing the maintenance operations (i.e., relamping).

Variable-speed drives used in combination with high-efficiency fan motors (both under installation in the Holland Tunnel) will provide significant energy cost savings. The CO level in the tunnel will determine the speed of the tunnel ventilation fans; a new CO monitoring and control system was also installed.

**VA CBBT:** The CBBT District switched to T-8 and T-5 lamps in its tunnels in 2000–2001. The project, which also raised the lighting a few inches, allowed the district to go from relamping once a week to once every two months.

**VDOT:** VDOT has considered a computerized maintenance management system.

**WSDOT:** WSDOT currently uses a specially designed truck for washing the walls of its existing I-90 tunnels. It uses maintenance management software as a tool to help manage tunnel and tunnel systems maintenance.

#### *2.3.3.2 Water Leakage*

Specialized technologies to address issues related to water leakage include vacuum injection of water seepage cracks, membrane-based waterproofing systems, plastic piping and heat trace to collect water leakage, installation of troughs, and water leakage management.

**Colorado DOT:** The EJMT utilizes basic technologies such as plastic piping and heat trace to collect water leakage.

Shortly after the HLT opened, a contractor was employed to use epoxy injection in some water seepage cracks. This treatment moved the water to other areas, abating the worst of the seepage and reducing it to small amounts.

**District DOT:** Water ingress at expansion joints has only been repaired through injection of hydrophilic polyurethane resin material. Water ingress at expansion joints has been controlled by installing a trough arrangement in the ceiling void to carry water to the walls, where it is piped through a wall and into the ventilation shaft drainage system. Vacuum injection of methylmethacrylate resin material has been used to stop water ingress through cracks.

**MassDOT:** MassDOT considers water leaks a management issue to only have in the most inert areas (e.g., away from electrical components and panels). Leaks damage electrical components and ducts; combined with exhaust, they create a corrosive environment. MassDOT developed a Wetness Chart as part of its tunnel water management process. Leakage checks are done for the tunnel structure, roadway, ceiling/overhead, supply air duct, cross passage, egress, and utility room. Ceilings are checked every month; other locations are checked every 12 months where needed and otherwise checked every three years. Ratings are 0 to 9 to be consistent with other ratings. A Wetness Report goes to the Leak Remediation Team for review and assignment of a priority rating. Due to the extensive tunnel system and its complicated geometry, its depth below groundwater, the construction methods used, and the large temperature swings of the tunnel structure, MassDOT spends a considerable amount of resources ($12 million a year) identifying and sealing tunnel leaks.

**PennDOT:** The PTC uses injection grouting, membrane, troughs, and chases as conditions warrant.

**PANY&NJ:** The PANY&NJ has typically addressed water leakage by grouting after construction of tunnels with standard segment liner design. It considers a membrane-based waterproofing system, providing the following design features are addressed:

- The waterproofing system must be continuous.
- The membrane must be able to adapt to irregularities in the surface attachment.
- The membrane must remain permanently impervious.
- The waterproofing must be able to bridge small cracks in the construction surface.
- The membrane must be resistant to aggressive water, whether from contaminated ground or biological influences.
- The membrane must be suitable for installation on damp and wet surfaces.
- The material must be self-extinguishing in case of fire.
- It must be possible to check and repair the membrane if required prior to placement of concrete elements in the final structure.

The above recommendations were developed for NATM applications.

**VA CBBT:** The CBBT District experiences some minor seepage on occasion, but those areas seal themselves through mineralization.

**WSDOT:** WSDOT has incorporated leak detection monitoring systems for all four of its floating bridges, but none for its tunnels. WSDOT has also developed a creative solution for leaks on its existing I-90 tunnels. It installed epoxy gutter systems to channel leakage water to drains and has sealed leaks with concrete sealer.

#### *2.3.3.3 Steel Fiber-Reinforced Concrete Liners for Rehabilitation*

While the use of steel fiber-reinforced concrete liners instead of prefabricated mesh reinforcement for rehabilitation is limited, no issues related to surface corrosion of the fibers or problems with fiber distribution have been identified. In one case, portions of monofilament fiber-reinforced ceiling lining delaminated due to expansion movement in two tunnels. Steel fiber-reinforced shotcrete has been used extensively in NATM applications.

**Caltrans:** Caltrans's only experience with fiber-reinforced tunnel lining was with a monofilament fiber reinforcement applied to the ceiling of two tunnels. Surface rust is not an issue with this product. However, several areas of the lining delaminated, and portions of the delaminated area fell off due to expansion movement of two adjoining sections. The lining's chemical bond was not sufficient to resist the mechanical forces. An anchored, prefabricated mesh would have limited the damage to a much smaller area and may have prevented the portions on the ceiling from falling.

**Colorado DOT:** In the HLT, The cast-in place-concrete lining protects the steel fiber-reinforced shotcrete.

**MassDOT:** MassDOT has not used steel fiber-reinforced concrete liners for rehabilitation.

**PANY&NJ:** Considerable research is being conducted on the development of concrete liners with steel fiber reinforcement and sprayed on waterproofing membranes. These technologies are being advanced primarily in Europe and are considered to be in the early stage of design implementation.

Steel fiber-reinforced shotcrete (SFRS) has been used extensively in NATM applications, and polypropylene fibers have also been included to provide increased ductility.

**VDOT:** To date VDOT has not used concrete liners with steel fibers.

**WSDOT:** For the AWV Tunnel precast liners, steel fiber reinforcement would be prohibited due to unpredictable strength characteristics, longevity, and quality control throughout the construction progress.

#### *2.3.3.4 Roadway Slab Over Plenum Rehabilitation*

None of the scan team hosts has done full-depth roadway deck replacements over plenums. Several have completed partial-depth deck replacements that utilized roadway deck panels to accommodate the temporary grade change due to the removal and replacement depth, or that simply patched with concrete and then placed a new wearing surface. Work was done either under full or partial lane closure during off-peak hours.

**Caltrans:** During a 2001 earthquake retrofit, the Posey and Webster Tubes were closed to replace the deck at expansion joints. While Caltrans has several tunnels with roadways over a plenum, none of the roadways has required rehabilitation.

**MassDOT:** MassDOT has not replaced a tunnel roadway deck to date.

**PennDOT:** PennDOT has inspected and analyzed concrete T beams that are supporting the roadway at Squirrel Hill. It has repaired T beam bridges by placing concrete and steel sister beams next to existing beams. PennDOT has also replaced the roadway slab at Ft. Pitt and Liberty, but those slabs do not have plenums underneath. Traffic was detoured for several months at both Squirrel Hill and Ft. Pitt to repair the roadways.

**PANY&NJ:** The PANY&NJ has not performed full-depth replacement of the roadway slabs in either of its tunnels. Where partial-depth replacement was performed, it used roadway deck panels to accommodate the temporary grade change due to the removal and replacement depth. The Lincoln Tunnel is done under full closure; the Holland Tunnel is done using single or double lane closure.

**VA CBBT:** The CBBT District has done partial deck replacement using simple concrete rehabilitation patching followed by placement of a new wearing surface. Repairs were performed at night under traffic with one lane open.

**VDOT:** The Elizabeth River Midtown Tunnel had a partial-depth replacement of its roadway slab using normal weight concrete. Repairs were performed under traffic during off-peak hours.

**WSDOT:** WSDOT has not replaced the roadway slabs in its tunnels.

## 2.3.4 Inspection

### *2.3.4.1 Improved Inspection Efficiency*

Various technologies have been used to improve efficiency in the inspection of tunnels, including:

- Laser surveys to establish baseline ceiling elevations
- Rotary delamination tools to sound vertical and overhead concrete surfaces
- Airflow test measurements for mechanical ventilation
- Impact echo to define delamination depths
- Side scan sonar and multi-beam sonar to aid inspection over underwater tunnel sections
- Signage installation for inspection location referencing

Access has been improved for inspection and maintenance by providing approved ladders and landings, and for confined space entry by providing adequately sized hatchways. Tunnel owners are streamlining the administration of generated inspection data and organizing logistics to better coincide with ongoing construction and maintenance activities; they are also using electronic database inspection systems with tablet computers and digital photography. The FHWA TMS is also used to improve inspection efficiency. In addition, several technologies have been considered to improve efficiency, including ground penetrating radar (GPR) and infrared thermography (IRT), and a tool for nondestructive testing of tunnel lining is currently being developed in the SHRP2 R06G research project. Figure 2.5 shows examples of the tunnel inspection equipment and access seen on the scan tour.

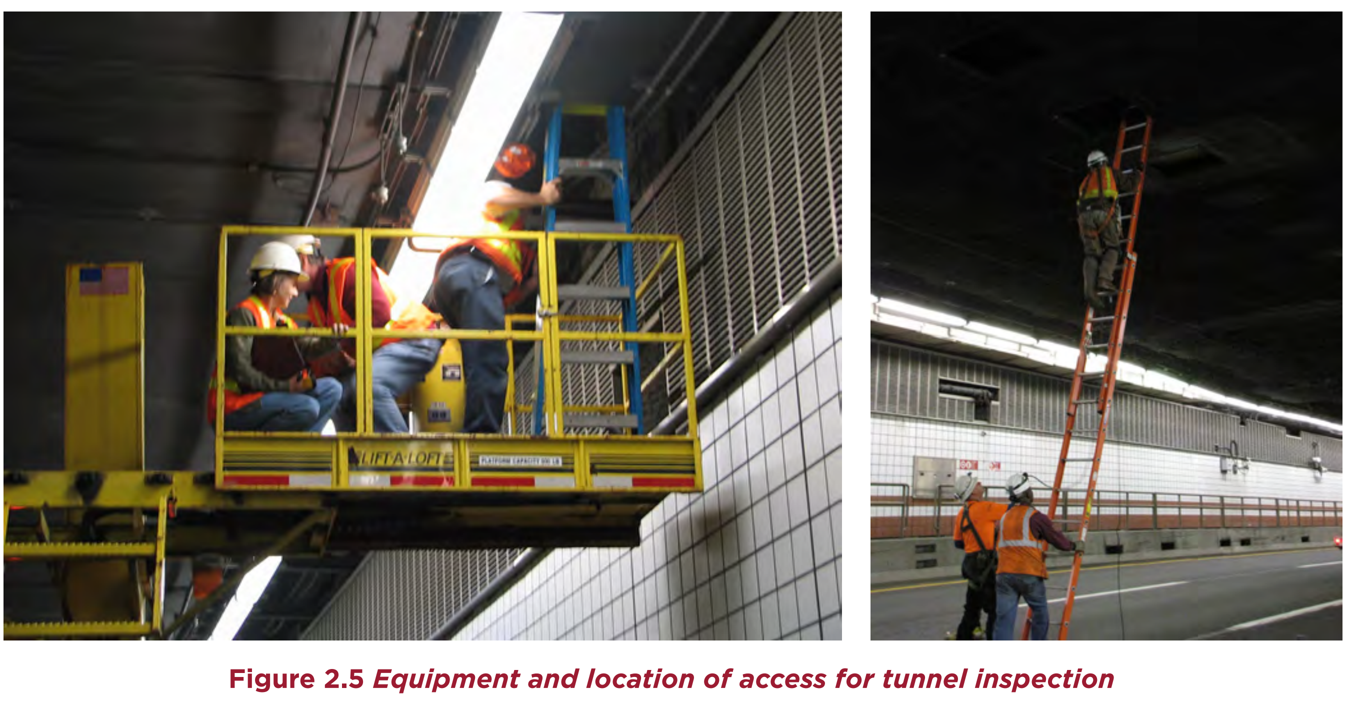


**Figure 2.5** ***Equipment and location of access for tunnel inspection***

**AKDOT&PF:** The AKDOT&PF has looked at other ways of conducting inspections but found no advantage over current techniques.

**Caltrans:** Caltrans has used a rotary delamination tool to sound vertical and overhead concrete surfaces. Personnel access for inspection and maintenance is always important. Features that improve both maintenance and inspections include providing Cal-OSHA approved ladders and landings, considerations to reduce the locations having confined space limitations, and adequately sized hatchways.

**Colorado DOT:** The EJMT used a laser survey in the tunnel interior to establish critical baseline ceiling elevations.

**District DOT:** DDOT is experimenting with the use of GPR but needs to do more testing before recommending its use. It has also used airflow test measurements for mechanical ventilation and has had specialty contractors evaluate thermographic and contact resistance testing for power distribution systems. It has also witnessed a contractor using impact echo equipment to fully define the depth of delaminations in the underlying mortar supporting the tile wall facing.

Using the FHWA TMS also improves efficiency in tunnel inspection, particularly on follow up inspections since the field forms are reused and the previous inspection data are available and ready for updating.

**MassDOT:** MassDOT has not used new technologies but is streamlining the administration of the data generated and the way it organizes the logistics to better coincide with normal, ongoing construction and/or maintenance activities. Installation of signage for location referencing for inspection and maintenance in tunnel roadways, hatches, doors, and plenum areas is improving both maintenance responses to inspection outcomes and the detail of condition assessment over time.

**PennDOT:** PennDOT has used electronic inspection forms with its in-house staff. It also uses FHWA's TMS for its consultant inspections.

**PANY&NJ:** The PANY&NJ has not used any new technologies to date.

**VA CBBT:** CBBT inspection is accomplished through a third-party engineering consultant. The CBBT District has developed and uses an electronic database inspection system that incorporates tablet personal computers and digital photography as key tools of the system. This system has been developed for use in tunnel interior inspection, data collection, and data management for inspection report preparation and repair recommendations. It is particularly useful in improving the efficiency of handling large volumes of data for preparing reports and recommendations. It has also used side scan sonar and multi-beam sonar to aid in inspecting and assessing protective fill and rock protection over underwater portions of the tunnels. Multi-beam sonar is very effective in efficiently obtaining accurate and comprehensive data over large areas; and computer software can then efficiently process and present that data.

**WSDOT:** WSDOT has talked to other owners about the merits of using IRT and GPR, but has received feedback that their experiences have not been that positive. Currently, WSDOT is hopeful that the current SHRP2-R06-G, NDT of Tunnel Lining may give owners some viable inspection options.

### *2.3.4.2 Electronic Methods to Document Conditions During Inspection*

Electronic methods used successfully to document conditions and deficiencies during inspections include handheld computers to collect inspection data in the field, electronic databases to record inspection findings, thermography to identify hot spots in panels, and dial gauge monitoring of hangers that are attached by epoxy anchors. Electronic methods used in M&E inspections include:

- Laser pointing temperature measurements for shaft bearings and electrical starter contacts to identify loose contacts and bearing condition trends
- Power meter analyzers for fan motor power measurements
- Portable measurements for motor winding insulation testing

GPR was used in the past (e.g., for inspection of embedded ceiling support features), but results were inconclusive due to problems interpreting the results. Some owners have expressed concerns about the reliability of GPR and IRT for inspection of slabs and walls in the tunnel environment.

**AKDOT&PF:** Currently deficiencies are recorded in a database for comparison. Any change in a negative direction is addressed as needed.

**Caltrans:** Although it is not electronic, Caltrans has used a rotary delamination tool to sound vertical and overhead concrete surfaces. The device works fairly well.

During M&E inspections, Caltrans has utilized the following:

- Laser pointing temperature measurements for shaft bearings and electrical starter contacts have been effective in finding loose contacts and bearing condition trends.
- Power meter analyzers for fan motor power measurements have been effective in measuring the extent of motor overloading from ventilation fan starting.
- Portable measurements for motor winding insulation testing that are documented on inspection reports are helpful for trend analysis.

**Colorado DOT:** NDT (radar) was used for the inspection of embedded ceiling support features in the EJMT. The results were inconclusive.

**District DOT:** DDOT uses handheld computers to collect data in the field during inspections. The data are then uploaded into the FHWA TMS, which has been customized for the DC tunnels. This system maintains all the condition data for the structural elements, including the inspector's field forms, photographs, and condition ratings for each element. Observations on the condition and operational characteristics of M&E equipment are also included in the database.

**MassDOT:** All inspections are visual, with bore scopes and NDT used as needed.

MassDOT is monitoring hangers monthly with dial gauges since the hangers are attached by epoxy anchors. MassDOT uses thermographic NDE for hot spots in panels.

**PennDOT:** PennDOT has not used electronic inspection methods on tunnels but has used GPR on bridge decks, with the results confirmed with chain drag. The PTC has had a GPR demonstration along with 3D survey collection but has not yet used it on a large-scale basis.

**PANY&NJ:** Inspection data are now hard copy and CDs but will be electronic in the future; reports are filed electronically. The PANY&NJ tracks priority work orders electronically and is looking at an asset management system to track costs. It has found the settlement data for the Holland and Lincoln Tunnels to be helpful in tracking changes that would otherwise be difficult to identify (e.g., silt accumulation, overloading, and hard points).

**VA CBBT:** The CBBT District has considered using GPR and/or IRT for nondestructive investigation of the tunnel slabs. It has also considered using IRT for the tunnel walls but is unsure of the reliability of the results in the tunnel environment and has used sounding instead.

**WSDOT:** The WSDOT mobile inspection program keeps all inspection findings in an electronic format. It has not used NDT to date.

#### *2.3.4.3 Access Equipment for Inspections*

Tunnel access equipment typically includes bucket trucks and scissor lifts for hands on inspections. Other access equipment includes truck-mounted platforms for rolling access to walls and ceilings, window washer-type platforms for inspection of high airshafts, tunnel lamping trucks, remote drain cameras, and personal monitoring equipment for confined space entry.

**AKDOT&PF:** The AKDOT&PF does not use specialized equipment. Its primary tools for inspection are a bucket truck and maintenance personnel.

**Caltrans:** Caltrans uses remote drain cameras to inspect drains and lift equipment, such as scissor trucks. Typical inspections for M&E equipment do not require specialized equipment for accessing electrical panels or visual inspection of bearings and power transmission equipment. Personal monitoring equipment is a requirement of and is used for confined space entry.

**District DOT:** DDOT uses various types of equipment, including bucket trucks and scissor lifts, to ensure close up inspections of the structural, mechanical, and electrical components, as necessary.

**MassDOT:** MassDOT uses bucket trucks and scissor lifts.

**PennDOT:** PennDOT uses a lift truck and tunnel lamping trucks to inspect the tunnels. It also has used a spider (a window washer type platform) to inspect the 200-foot-high airshafts in the Liberty Tunnel.

**PANY&NJ:** The PANY&NJ has not required special accessing equipment.

**WSDOT:** The WSDOT uses truck-mounted platforms for rolling access to the walls and ceilings of tunnels.

### 2.3.5 Operations

#### *2.3.5.1 Incident and Speed Detection, Smoke Detection, Back-up Power, and Automated Incident Response Systems*

Short minor tunnels frequently do not have automated systems. However, major tunnels have a variety of automated systems as described below.

- **Incident and speed detection systems** include automated video incident detection systems that have traffic monitoring CCTV cameras integrated with the operations center and local highway patrol; induction loops embedded in the roadway for speed detection; over-height detectors for tunnel strikes; and lane signals augmented with public address systems, HAR, radio rebroadcast systems, VMSs inside and outside the tunnel, and movable medians and boom gates
- **Smoke detection systems include** CCTV monitoring, detecting rising CO, stopping traffic, and using dedicated call boxes fed directly to the operations center. Also included are linear heat, CO, hydrocarbon, and air speed detectors with smoke and fire indication alarms, although their effectiveness is questioned. One tunnel owner installed a foam suppression system that was subsequently turned off because of false alarms and preferred alternative technology.
- **Backup power systems** include uninterruptible power supply (UPS) and standby generators for critical systems such as ventilation fans, lights, and drainage pumps; emergency generators operated on natural gas; fully redundant servers; and power from different power companies through different substations, with oil-fueled emergency generators as further backup.
- **Automated incident response** include CCTV cameras, motion detectors, and open door alarms fed to operation centers for security and intrusion response; lane control signals and ventilation control integrated with fire-detection in accordance with NFPA 502 for automated incident response; and incident response management fully integrated with traffic and facility management, including VMSs, CO and hydrocarbon sensors, ventilation control, pump station monitors, HARs, over-height vehicle detectors, and two-way radios.

**AKDOT&PF:** Currently the AKDOT&PF monitors the tunnel environment using CO monitors, inductive loops, remote traffic microwave sensors, speed radar, heat detectors, and cameras. These devices, with the exception of the speed radar, are integrated into the Tunnel Control System. The remote traffic microwave sensors report speed to the operator. Should the devices detect a state that is outside the norm, the system will alert the operator. Should a detected state fall into a dangerous level, the system will alert the operator and start shutting traffic down.

Backup power consists of a UPS and generators. The backup power engages if line power is lost.

**Caltrans:** All Caltrans tunnels that are major tunnel systems have traffic monitoring CCTV cameras with pan, tilt, and zoom capability and send the feed to the local California Highway Patrol/TMC and to the local maintenance OMC. The tunnels also have CCTV cameras for security and intrusion monitoring; this feed is also sent to the OMC. Shorter, minor tunnels do not have visual monitoring.

Speed detection is done with induction loops imbedded on the roadway.

Smoke detection is accomplished with operators visually monitoring CCTV, detection of rising CO, traffic stopping, and use of dedicated call boxes that feed directly to the OMC operators. The linear heat detectors in most of the newer minor-sized tunnels also give smoke/fire indication alarms, although Caltrans questions the system's effectiveness[31].

The backup power systems are independent substation power feeds; stationary standby generators for full lights, ventilation, and controls; and stationary standby generators exclusively for emergency lighting and controls.

The two newest tunnels still in design and one in construction will employ video imaging detection technology for traffic monitoring and smoke detection only as a backup detection system. Caltrans is using this relatively new system to test its effectiveness; this will be its first application.

**Colorado DOT:** The EJMT utilizes a video surveillance system with over 100 color cameras with pan, tilt, and zoom capability situated strategically around the facility. CDOT has two 500 kW emergency generators that operate on natural gas, as well as UPS systems for critical systems. The EJMT has a CO detection system that is monitored constantly from the control room, and the ventilation system is adjusted to obtain optimal CO ranges and tunnel opacity. The EJMT utilizes four over-height detectors to eliminate tunnel strikes.

The HLT has multiple redundant systems that monitor both the approaches and bores. Loop detectors and cameras are used to monitor traffic for accidents or obstructions. Environmental monitoring is accomplished via linear heat, CO, hydrocarbon, and air speed detectors. The HLT receives its power from two different power companies through two different substations. Currently the tunnel power consumption is split between the two, but the switchgear will automatically tie one side to the other if one fails. If the HLT lost power from both companies, its oil-fueled emergency generator would power everything except the tunnel ventilation fans. The HLT also has emergency power units that will power every seventh light in the bore for approximately one hour; a UPS protects its sensitive/critical equipment.

**District DOT:** DDOT has linear heat sensors for fire-detection in larger tunnels (the system incorporates rate of rise and fixed temperature detection). Its lane control signals are integrated with fire-detection in accordance with the requirements of NFPA 502 for automated incident response. Its ventilation control is also integrated with fire-detection for automated incident response. Its fire panel, ventilation controller, and lane signal controller incorporate

[31] No other product meets NFPA 502 guidelines.

battery backup or individual UPSs. DDOT has no smoke detection in roadway areas, and no speed detection.

Lane control signals are a recent addition to the tunnels. DDOT's experience in tunnels shows that signals alone are rarely effective in influencing motorist behavior. In order to effectively influence motorist behavior in an incident scenario, it has found that lane signals need to be augmented with other technologies (e.g., public address systems, radio rebroadcast systems, VMSs [both outside and inside the tunnel], and movable medians/boom gates).

**MassDOT:** MassDOT has implemented an Integrated Project Control System (IPCS) in which incident response management is fully integrated with traffic and facility management. The IPCS includes VMSs, CO and hydrocarbon sensors, ventilation control, pump station monitors, HAR, over-height vehicle detectors, and two-way radios. The HOC monitors and controls the systems using two fully redundant servers. Two additional fully redundant servers are available as backups and can be running within 20 minutes. MassDOT is now working to improve the IPCS data reporting capabilities.

The IPCS relies on highly customized proprietary software and nonstandard field equipment. As a result, MassDOT has aging field equipment that requires constant testing. It has upgraded the operating system three times over the 10-year life of the system; the last upgrade required $4 million and two years to install. The main task during these upgrades was testing, due to the system's complexity. MassDOT now has a full contingency of test plans that can be modified or added as needed to make further development processes easier in the future. MassDOT plans to integrate the standalone systems into a common system and then eliminate the standalone systems.

MassDOT has separate systems for security (i.e., cameras, motion detectors, and open door alarms) that feed back to the HOC; these systems will be integrated in the future. It also has roadway and security cameras; although the two systems are discrete, each can look at the other's area during an incident. MassDOT built a portal on the Internet to allow the public to access traffic cameras for a fee. Cameras are set to look downstream to avoid headlights.

MassDOT is installing a system to detect incidents automatically by CCTV. The DOT has its own tow trucks and incident response stations.

A foam suppression system was installed in an existing tunnel prior to the CA/T project. The system was turned off several years ago because of false alarms and because MassDOT now has cameras and other means of protection.

MassDOT has backup power systems for its M&E equipment, including emergency generators, tunnel lighting UPS batteries, and pumps.

**PennDOT:** PennDOT uses ITS cameras for incident detection, generators for backup power, and batteries for AC backup power at Ft. Pitt. The City of Pittsburgh is installing cameras at the city side portal for crime detection purposes. PennDOT has also upgraded lighting ventilation, and electric equipment, which lowered utility bills. The PTC is placing CCTV throughout, along with heat and speed detection to supplement manual alarms.

**PANY&NJ:** The PANY&NJ tunnels are equipped with CCTVs and monitored 24/7 via manned control rooms.

The design of the electrical power distribution system for PANY&NJ tunnels maximizes the redundancy of the system by employing two different utility companies to provide service to the tunnels. The automatic load transfer of the lighting and ventilation systems ensures the tunnels' continued operation.

The Lincoln and Holland Tunnels also utilize ITS to detect incidents within the tunnel tubes. The system assists the communications desk personnel in quickly identifying incidents and dispatching response personnel.

**VA CBBT:** Police cars equipped with radar monitor the CBBT facility 24/7. The CBBT District also has a video camera system monitored by operators in the ventilation buildings on two of the islands. In addition, the CBBT District has backup power capabilities at each island, one for each approach side of the two tunnels (i.e., four total). This backup consists of generators and UPS systems that control ventilation fans, tunnel lights, and drainage pumps in both portal and mid channel pump rooms. There is also a CO detection system that is constantly monitored by the operators, with the ventilation system adjusted to accommodate optimal CO ranges.

**VDOT:** VDOT has incident detection with CCTV, speed detection with loop detectors embedded in the asphalt riding surface for vehicle counts, ITSs consisting of cameras and VMS boards, visual smoke detection, and backup power systems for emergency lighting using UPS and diesel generators. Collected data are provided to control room personnel for operational response. VDOT does not have automated incident response.

**WSDOT:** In existing long tunnels, WSDOT uses traffic loops and surveillance cameras for incident detection. It uses blank out signs, HAR, radio rebroadcast, and VMSs for ITS systems. It uses alternate utility supply, generators, and UPS for backup power supplies. It does not currently use smoke detection or automated incident response. For its proposed SR 99 tunnel it is considering full-color, full-matrix signs and the capability for variable speed limits, over-height detection, smoke detection, and automated incident response.

#### *2.3.5.2 Detection and Prevention of Hazardous Cargo Entering Tunnels*

Toll-booth attendants, manned inspection stations, traffic control (e.g., signage at approaches), dedicated local and state law enforcement, and undisclosed technologies are used to detect and prevent hazardous cargo from entering tunnels. This cargo has restricted access (e.g., during specified times of the day) based on vehicle code ordinances. VMSs and public press releases inform truckers of access restrictions.

**AKDOT&PF:** AKDOT&PF uses toll-booth attendants, traffic control, and law enforcement to scan vehicles for compliance..

**Caltrans:** Caltrans has vehicle code ordinances to restrict access of hazardous cargo trucks (e.g., restricted hours, inspection and escort, and prohibited access).

**Colorado DOT:** The EJMT prohibits hazardous cargo most times of the year. When hazardous cargos are allowed, CDOT relies on visual identification.

**District DOT:** DDOT uses fixed signage on the approaches to the tunnel.

**MassDOT:** MassDOT prohibits hazardous materials from entering its tunnels, and its dedicated state police troop enforces this restriction. In the past, police turned trucks around through an opening in the barrier; now the police escort them through the tunnels and charge the truckers for the entire process. The police did an outreach program to the truckers before the policy was implemented.

**PennDOT:** Explosive and flammable loads are prohibited in PennDOT tunnels.

**PANY&NJ:** No hazardous cargo is allowed in the tunnels. The Port Authority Police monitor vehicles entering the tunnels for hazardous cargo using undisclosed technology.

**VA CBBT:** The CBBT District prohibits various explosives, poisonous gases, and substances that are dangerous when wet or inhaled.

**VDOT:** VDOT has staffed inspection stations.

**WSDOT:** At times there are flammable restrictions for vehicles entering I-90 tunnels, and WSDOT uses VMSs and public press releases to inform truckers of these restrictions. State and local law enforcement is used to detect vehicles entering the tunnels.

#### *2.3.5.3 Utility Cost Efficiencies*

Strategies to achieve utility cost efficiencies include:

- Installing new, more efficient lighting, light fixtures, and lighting controls
- Employing variable speed drives combined with high-efficiency fan motors
- Adjusting control algorithms to ensure that the fans run and lights are on only when needed
- Testing sprinkler systems without discharging water
- Bleeding water lines yearly instead of quarterly
- Requiring cell phone companies to install separate meters and pay for their own power
- Conducting energy audits
- Aggregating procurements

**Caltrans:** Caltrans has a rehabilitation contract for the Posey and Webster Tubes and the Caldecott Tunnel Complex to replace the aging ventilation fan motors and controls with inverter rated motors and variable frequency drive controls. An upgraded SCADA system will also be included to monitor the tunnel operations and control fire/life-safety systems. In the same tunnels, Caltrans has also installed new HPS light fixtures and lighting controls. It expects significant electrical power savings from these measures.

**Colorado DOT:** CDOT is in the very early stages of energy audits. It has entered into a contract with an energy savings company and anticipates improved efficiencies.

The HLT has been installing electronic ballasts in the bores as needed as well as replacing T 12 florescent lights with the new energy-efficient T-8 lights in the Cinnamon Creek Complex. It is currently looking at retrofitting the existing florescent light fixtures in the bores with new energy-efficient technology lights. This would reduce HLT electrical costs by as much as $50,000 a year.

**District DOT:** DDOT plans to look at this issue in the future. Its ventilation system review could possibly lead to reduced energy consumption since from midnight to 5 a.m., far more ventilation effort is used than is required. However, if the number of fans running at night is reduced, the restarts for the morning peak need to be managed to avoid escalating peak demand charges.

**MassDOT:** MassDOT uses approximately 133 million kilowatt hours (kWh) a year for lighting and to operate the ventilation system at 15 percent capacity on average, for a total cost of $12 million a year. Last year it aggregated procurement with other state agencies and authorities in order to lower these costs.

**PennDOT:** PennDOT has required cell phone companies to pay for their own power since 1997 (the power company installed separate meters).

**PANY&NJ:** The PANY&NJ achieved cost savings by employing variable-speed drives combined with high-efficiency fan motors and by using efficient lighting and controls.

**VA CBBT:** The CBBT District judges each utility on its own merits as the need arises with the latest industry standards. Set standards for cost efficiencies are not written.

**WSDOT:** To achieve electric utility cost efficiencies, WSDOT has reduced fan and light usage on its existing I-90 tunnels by adjusting the control algorithms to ensure that the fans run and lights are on only when needed. It also now tests sprinkler systems without discharging water and bleeds water lines yearly instead of quarterly to reduce water utility charges.

### 2.3.6 General

#### *2.3.6.1 Other Advanced Technologies under Consideration*

Other advanced technologies that tunnel owners are considering include:

- Computer systems that allow the operator to access and control all tunnel functions in a local maintenance district
- Zoned deluge sprinkler fire protection

- An over-height vehicle-detection system that activates an electronic display sign and captures the violators' U.S. DOT vehicle number
- Automated over-height protection and enforcement system
- Stainless steel transition ceilings designed to slow over-height vehicles
- Lane control signals that use radio communications to transmit commands from the main transmitter/controller to small receivers at each bank of signals
- Integrated portal mounted VMSs with fire-detection system
- European signage that includes green exit lights and the image of a person running with distance shown
- Large-diameter TBM technology
- Full-color, full-matrix signs

The use of wind energy was evaluated but no viable solution was found.

**Caltrans:** Caltrans' two newest tunnels still in design and one in construction will employ video-imaging-detection technology for traffic monitoring and smoke detection as a backup detection system only. Caltrans is using this relatively new system to test its effectiveness; this will be its first application.

The Caldecott OMC SCADA computer will allow the operator to access and control all functions of the other 12 tunnel bores in the local maintenance district, which will be connected via the Internet.

The Doyle Drive tunnel complex will include zoned deluge-sprinkler fire protection. This is Caltrans' first application of this system.

**District DOT:** DDOT is using an automated over-height protection and enforcement system.

DDOT's recently installed lane control signals use radio communications to transmit commands from the main transmitter/controller to small receivers at each bank of signals. This method of communication simplifies installation in operating road tunnels. The signals themselves were developed specifically to be large enough to command motorist attention, but small enough to keep damage from over-height vehicles to a manageable level. DDOT believes that the system is ideal for use in existing tunnels, particularly those with clearance constraints.

DDOT is considering integrating portal mounted VMSs with the fire-detection system. The combination of red signals and a text display on the message signs will help stop motorists from entering the tunnel during an emergency scenario.

DDOT has a system in place that detects over-height vehicles and activates an electronic display sign. The system also captures the U.S. DOT number of vehicles violating the tunnel's 13-foot height restriction. The over-height detection system could also be integrated with the portal-mounted message signs and portal lane signals to help prevent over-height vehicles from entering the tunnel.

**MassDOT:** Installation of automatic video incident detection equipment has vastly improved detection time for MassDOT tunnel incidents. Over 600 cameras cover the MassDOT tunnels system and are viewed by an average of three control center staff. The use of the automated video incident-detection system has greatly improved MassDOT's incident-detection capabilities and improved response time to avert larger impacts.

**PennDOT:** PennDOT is considering using ideas from the 2005 European Tunnel Scan (e.g., green exit lights, green directional signing during a fire, and the image of a person running with a distance shown).

**PANY&NJ:** The PANY&NJ believes that the most significant development in TBM technology worldwide is the apparent increase in tunnel diameter. The recent successful installation of two 50-foot-diameter tunnels across the Yangtze River in China (one year ahead of schedule) was a remarkable tunneling achievement. It is believed that this trend of increasing tunnel diameter will impact future tunneling projects in the U.S.

To help address over height detection issues, the PANY&NJ developed stainless steel transition ceilings designed to slow down the over-height vehicle, rather than having the vehicle come to an abrupt stop. This has drastically reduced damage within the tunnel from over-height vehicles while likely reducing injury to the drivers and passengers in the other vehicles.

**VA CBBT:** The CBBT District continually looks for ways it can improve its facility while achieving greater cost efficiencies. In 2009 it looked at both wind energy and LED lighting. Wind energy presented no viable solution for their facility. It is testing some LED fixtures on the bridge, but not in the tunnels at this time. Its current goal is to achieve a 50 percent reduction in energy costs with a 10-year payback for the fixtures.

**WSDOT:** WSDOT has considered using LED fixtures on proposed and current tunnels to reduce tunnel power requirements, but has not found lighting fixtures that can provide the required lighting levels. It has experimented with replacing HPS fixtures with LED fixtures for a section of one of its existing I-90 tunnels; however, the existing housings were not suitable for LED fixtures. WSDOT has recently upgraded its old tunnel control system with a more modern tunnel control system.

For the new SR 99 tunnel it is considering using incident-detection and smoke-detection software to enhance the capabilities of its fire response times. It also plans to use full color, full-matrix signs in the tunnel to convey lane control, warnings, and speed limits. It is also planning to install a semi-transverse, single-point-extraction ventilation system that will also use jet fans above the tunnel's roadway, entrance, and exit.

### 2.3.6.2 Additional Recommended Specialized Technologies

Addition specialized technology applications that tunnel owners would recommend include:

- Computer analysis of hazardous, security, and fire/life-safety alarms
- Internet-based SCADA and monitoring
- Radio rebroadcast and public address systems that enable tunnel operators to communicate with motorists during emergencies and to manage congestion resulting from minor accidents
- Deluge systems to control the spread of fire and minimize smoke generation
- Luminance meters to adjust lighting levels at portal transition areas
- Fuel-cell UPS systems for lower testing and maintenance costs than with battery powered UPS systems
- Fusible panels to increase exhaust flow directly from an incident area
- Data-logging systems for monitoring individual system activities
- Wall panels that consist of a thin piece of metal with porcelain baked into the metal instead of tile for aesthetics, reflective qualities, and ease of replacement
- In-pavement lighting for channelization

**Caltrans:** Computer analysis of hazardous, security, or fire/life-safety alarms, and Internet based SCADA and monitoring, are still seen as emerging technology. These applications are expensive and force the acceptance of increased liability to achieve the desired detection. Caltrans is slowly adopting these new applications, but successful experiences will be needed before wide acceptance is achieved.

**District DOT:** Tunnels of sufficient length to warrant fire-detection and ventilation systems should be equipped with radio rebroadcast systems and public address systems that enable tunnel operators to communicate with motorists during emergency scenarios. These systems can also be used to manage congestion resulting from minor accidents or breakdowns. New tunnels of sufficient length to warrant fire-detection and ventilation systems should include deluge systems to control the spread of fire and minimize smoke generation.

**MassDOT:** Luminance meters that control lighting circuits utilizing LPS light fixtures to adjust lighting levels at portal transitional areas are helpful. MassDOT tunnels use over 10,000 batteries in various UPS systems for tunnel lighting and ventilation. Fuel-cell UPS systems may enable MassDOT to avoid some of the testing and maintenance costs associated with battery powered UPS systems.

**PANY&NJ:** The PANY&NJ tunnels are equipped with fusible panels to increase exhaust flow directly from an incident area.

**VDOT:** VDOT recommends data logging systems to monitor individual system activities (e.g., fire pumps, ventilation fans, drainage pumps, CO alerts, and hydrocarbon detection in wet wells).

**WSDOT:** WSDOT is considering using wall panels instead of tile for its proposed tunnel. The panels consist of a thin piece of metal with porcelain baked into the metal. The panels are aesthetically pleasing, have the reflective qualities needed for tunnel lighting, and are easily replaced if damaged. WSDOT has also used in-pavement lighting for channelization in one of its short tunnels on SR 20.

CHAPTER 3

# Recommendations And Implementation Plan

## Introduction

The scan team identified a number of highway tunnel initiatives or practices of interest for nationwide implementation or for further evaluation for potential nationwide implementation. The implementation of the scan team's top eight recommendations will be a step in the process of developing national standards and guidance. Scan findings will also provide data for consideration in the development of a national tunnel inventory. These activities will assist the AASHTO SCOBS T-20 and the FHWA in developing best practices for roadway tunnel design, construction, maintenance, inspection, and operations of existing and new tunnels.

The lead group for implementation of scan recommendations is anticipated to be T-20 in conjunction with FHWA and the TRB AFF60 working in conjunction with NFPA and other tunnel organizations.

The scan team initially presented its findings and recommendations to T-20 during the January 2010 TRB Annual Meeting. Scan team efforts also include distribution of the FHWA tunnel safety brochure that was developed following the 2005 international tunnels scan and providing additional information on the FHWA tunnels Web site. Other activities include coordination and development of research statements related to tunnel needs. To disseminate information from the scan, the team is giving technical presentations at national meetings and conferences sponsored by FHWA, AASHTO, and other organizations; hosting webinars; and is planning to write papers for various publications. The full implementation plan with detailed implementation strategies can be obtained through T-20.

## Strategies and Actions

The implementation plan strategies and activities for the scan team's top eight recommendations are described below.

### 1. Develop standards, guidance, and best practices for roadway tunnels

Design criteria for new roadway tunnels should consider:

- Performance-based construction specifications
- Design recommendations for extreme events (manmade and natural [e.g., seismic and storm events]) and tunnel security (e.g., blast resistance and lifeline requirements)
- Design criteria for vertical clearance, horizontal clearance, and sight distance
- Criteria for tunnel design life and future maintenance for structural, mechanical, electrical, and electronic systems

- Criteria for new tunnel load rating
- Seismic design criteria for one level versus two level design events
- ADA requirements for emergency egress[32]
- Placement and layout of the tunnel operations center
- Fire and life-safety systems in tunnels

Rehabilitation of existing tunnels should consider obsolescence, tunnel design life, high performance materials, and existing geometry to maximize safety, system operation, and capacity.

Tunnel systems are generally complex and expensive in terms of capital costs. It is critical that any emergency response plan includes the basis of design for how the structure and systems were designed to operate; without this information, the response plan may be incorrect. The use of peer review teams and technical advisory panels with subject matter expertise should be considered in developing site-specific criteria. Risk management of complex systems is important, as is system redundancy. The SCADA system can be programmed to monitor and control redundant systems and structures.

Contract guidelines for roadway tunnels need to be developed to accommodate the various procurement methods (e.g., design-bid-build, design-build, and design-build-operate-finance), considering to the extent applicable the Underground Construction Association's Recommended *Contract Practices for Underground Construction*[33].

Design and construction standards and guidelines need to be developed for tunnel construction methods, such as the use of TBMs versus conventional tunneling, design criteria that include seismic design, and lifeline requirements. Conventional tunneling methods include the SEM or NATM, the ADECO method, and the cut-and-cover-method.[34].

Some of the above topics will be addressed in an NCHRP project that began in 2010 and is sponsored by the AASHTO Subcommittee on Bridges and Structures. The project is developing LRFD specifications and guidance for new and existing tunnels.

### *Implementation Strategy*

The implementation strategy for developing national design standards, guidance, and best practices for roadway tunnels will include research, technical presentations, workshops, and coordination with multiple agencies and tunnel owners. Strategies developed for implementation will include structural, mechanical, electrical, and roadway tunnel geometric needs identified in the scan. Coordination with the NFPA will be essential in developing standards and guidance, especially in the area of electrical

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[32] The ADA does not currently apply to tunnels.

[33] *Recommended Contract Practices for Underground Construction,* ed. William W. Edgerton, Underground Construction Association of the Society for Mining, Metallurgy, and Exploration, , 2008

[34] Lifeline requirements, which can vary among agencies, recognize the need for certain routes and key facilities (e.g., bridges and tunnels) to be operational immediately or shortly after a major incident or event, such as an earthquake.]

and mechanical systems used in roadway tunnels. Strategies will be developed for both new and existing roadway tunnels.

Strategies for preliminary design of roadway tunnels will include developing guidance for site-specific design criteria, national standards, and construction methods. Design standards, guidance, and best practices should include consideration of maintenance, inspection, and operation of roadway tunnels.

### 2. Develop an emergency response system plan unique to each facility which takes into account human behavior, facility ventilation, and fire mitigation

A fire ventilation study should be performed and a fire ventilation plan developed and adopted for each facility. To adequately address emergencies, a tunnel's design should take into account the realistic spread of fire, smoke, toxic gases, and heat in the tunnel and the effect of different types of ventilation systems on the fire, including fire suppression, if the tunnel is so equipped. Fire mitigation should include spill control.

In general, the scan team found that facilities should improve their procedures to direct the public to safety. The fire plan should be consistent with the motorists' various responses to a fire, and the operation of all tunnel fire response systems should be consistent with this behavior. Enhancements to direct the public to safety (e.g., better signage and intelligible public address systems) should be considered, including the recommendations for these that were made in the 2005 international tunnels scan.

Further research is needed to understand how fire and smoke spread in a tunnel and how people react in emergencies. The scan team recommends that the research topics related to fire that were developed during the AASHTO workshop on tunnel safety and security research needs (November 2007, Irvine, California) should be considered.

#### *Implementation Strategy*

The implementation strategy includes assembling available information from around the world on tunnel fires, the spread of smoke, and human behavior during such instances, both from actual tunnel fires and from research conducted on these topics. Additionally, collecting data on fire and life-safety systems and components will be important. Critical items in gathering information are the basic assumptions for design fires for each individual tunnel; this may be relatively simple, but will define the emergency operation procedures.

Once the information has been assembled, areas that need further study will be identified and research conducted to fill these knowledge gaps. Example emergency response plans can then be prepared to incorporate and illustrate the application of this knowledge base. These example emergency response plans will be shared with FHWA, tunnels owners, NFPA, academia, and industry.

Training programs based on the research and example plans need to be made available to tunnel owners. This training will help them understand their tunnel operating environment and the potential dangers and help them assess the effectiveness of their current emergency response plans. Owners will then have the knowledge needed to adjust their emergency response plans and improve the visual and audible guidance that tunnel users are given in an emergency

### 3. Develop and share inspection practices among tunnel owners

The scan team found that the best tunnel inspection programs have been developed from bridge inspection programs. In many cases, bridge inspectors also perform the structural inspection of tunnels. Therefore, the team recommends that tunnel inspection programs be as similar as possible to bridge inspection programs.

Those components of the tunnel that carry or affect traffic (e.g., roadway slabs and floor systems that carry traffic) should be load rated in accordance with the AASHTO *Manual for Bridge Evaluation*[35] to the extent possible. In the analyses, different operational conditions should be considered. Structural analyses should be performed on non-traffic-carrying components (e.g., plenums, plenum walls, and hangers) as their physical conditions change, as they are modified, and as the loads that they are to be subjected to change (e.g., air forces if fans are upgraded).

Recommended practices for inspection frequencies, minimum code requirements, and a federal coding manual need to be developed. Current practice is a frequency of one to five years for structural inspections and daily to yearly frequencies for mechanical and electrical (M&E) inspections, depending on the level of inspection. Maximum frequencies should be set, and owners should be encouraged to develop actual frequencies based on manufacturer requirements and a risk-based analysis of hazards due to condition, deterioration, and performance history. If the inspection frequency is less than accepted best practices and standards, the owner will take on liability. Inspection frequency should be based at least partially upon the level of risk.

A baseline data inventory for tunnels needs to be developed for submission to the FHWA in conjunction with NCHRP 20-07/Task 261, (Best Practices for Implementing Quality Control and. Quality Assurance for Tunnel Inspection), Task 4[36].

Inspection practices need to be shared among tunnel owners in five areas:

1. The scan team identified a best practice for the inspection of submerged tunnels using multi-beam sonar scans.
2. Tunnel inspection training that takes into consideration all aspects of the tunnel structure and systems needs to be developed.
3. Tools to find voids behind tunnel linings need to be developed..
4. Coordinated overnight tunnel closing should be done so that as much maintenance and inspection as is possible can be done.
5. Best inspection practices should be shared.

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[35] *Manual for Bridge Evaluation*, AASHTO, 1st Edition, 2008

[36] "Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspection," NCHRP 20-07/Task 261, October 2009, http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2474

### *Implementation Strategy*

The implementation strategy will focus on working with FHWA to create a highway tunnel inspection program for the country that is at least equal to the existing NBIS[37] for highway bridges. This includes providing input to the Proposed Rule Making for the National Tunnel Inspection Standards[38] during the comment period, assisting FHWA in developing a federal coding guide, developing a federal inspector training manual and updating previously published manuals, developing a federal computer data system and initial tunnel database from previous studies, and developing a manual for tunnel evaluation.

## 4. Consider inspection and maintenance operations during the design stage

The scan team found that inviting all disciplines to provide their input during the design phase results in a better product. The design of a tunnel should address future inspection and maintenance of all tunnel systems and equipment by providing for adequate, safe, and unimpeded access to all components. This can be accomplished by bringing together all engineering disciplines that will be accommodated in the tunnel. While the scan team understands that tradeoffs must be made between access and a practical design, these tradeoffs could have cost and safety implications for maintenance and inspection over the life of the tunnel.

### *Implementation Strategy*

The implementation strategy focuses on educating prospective tunnel owners and tunnel designers on the inspection and routine maintenance needs that a tunnel will require once it is built to keep it safe and operational. Specific strategies include:

- Assembling best practices and lessons learned to be shared among owners and designers
- Incorporating discussions of inspection and maintenance in guidelines and documents, such as the AASHTO *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*[39] and the proposed tunnel design code
- Providing technical presentations on this topic
- Providing a panel of experts who could be called upon to assist designers by reviewing preliminary plans for tunnels and providing recommendations for improving access

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[37] "National Bridge Inspection Standards," U.S. Department of Transportation, FHWA, Federal Register, Vol. 69, No. 239, pp. 74419–74439, December 14, 2004, http://www.fhwa.dot.gov/bridge/nbis.htm

[38] National Tunnel Inspection Standards, Advance Notice of Proposed Rulemaking, FHWA, Federal Register, November 18, 2008.

[39] *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*, AASHTO, August 2010

The work implementing the strategy for this recommendation also feeds into the scan team's implementation strategies for recommendations 1 (develop standards and guidance), 3 (develop and share inspection practices), and 7 (share existing technical knowledge about tunnel design).

## 5. Develop site-specific plans for the safe and efficient operation of roadway tunnels

A concise site specific tunnel operations manual needs to be developed. It should include the design assumptions for fires and other hazards, ventilation procedures, traffic control guidelines, and general maintenance procedures (e.g., washing guidelines and fan and bearing maintenance). The manual should also include training guidelines and training schedules for all personnel and should reference the incident response manual for incident response procedures and training.

Tunnel owners should implement state-of-the-art video surveillance and communication systems, which provide numerous benefits (e.g., incident response, traffic management, and increased security). The scan team found a best practice of lane closure or changing traffic direction (e.g., pneumatically activated lane delineators and zipper barriers that provide for reversible lanes and barriers through tunnels and tunnel approaches). The owners should have an operating procedure that considers safety both for the public and for the owners' personnel.

An incident response manual, separate from the operations manual, should be developed to outline procedures that will require various community, police, fire, and emergency services response in the event of incidents that disrupt traffic and/or increase risks. Periodic drills, including tabletop exercises with appropriate agencies, should be performed.

The scan team findings support restricted transportation of hazardous cargo through tunnels. In the event that no alternate route is available, well defined emergency response and fire ventilation plans should be in place. Restricting the hours during which hazardous cargo can be transported through tunnels is an option (e.g., from 3 a.m. to 5 a.m. under controlled conditions). The scan also found several preventive operational strategies for hazardous materials; these are covered in Chapter 3.0.

### *Implementation Strategy*

The implementation strategy for this recommendation includes contacting the owners of major U.S. tunnels in order to provide guidance regarding site specific needs related to tunnel operations and tunnel incident management. Specific activities will include assisting in developing:

- A concise site specific operations manual that will outline the recommended best practices of tunnel operations
- A separate incident response manual to facilitate effective communication and performance during emergency conditions, including making recommendations regarding drills and tabletop exercises with local entities relative to incident response
- Fire response and fire ventilation plans, including describing and emphasizing the importance of video surveillance and effective communication systems in major tunnels.

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Recommendations on proposed guidance for these activities will be provided to the AASHTO Technical Committee for Tunnels, T-20

## 6. A tunnel includes a long term commitment to provide funding for preventive maintenance, system upgrades/replacements, operator training and retention

The decision to build a tunnel is a long term commitment on the part of the owner. Tunnels that include 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. The AASHTO SCOBS should establish a target level of condition, system reliability, and performance for the facility to guide operators and owners on current and future decisions that will require manpower or funding.

As equipment ages, system components will become obsolete and replacement parts will be difficult to find. In particular, electronic equipment, such as computers, SCADA systems, and sensors, becomes obsolete or is no longer supported by its original manufacturer sooner than mechanical equipment does. Periodic upgrades are vital to keep all systems functioning reliably. For these reasons, funding 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.

Owner agencies should develop tunnel preservation guidelines for funding purposes (e.g., for concrete repair and washing of walls).

A separate fund should be dedicated to tunnels, and agencies should work with local funding, planning, and maintenance organizations to accomplish this task. The financial management plan for tunnels should not only include initial costs for construction, but should also address future preservation and upgrading needs. The scan team found that without this dedicated fund, tunnel upgrades do not compete well with system wide needs, such as traffic signals and pavement preservation.

Training, retention, and a succession plan should be developed for tunnel operators. The scan team found best practices that fostered pride of ownership, a “home away from home” culture and “can do anything” attitude.

### *Implementation Strategy*

A tunnel is an underground highway that in many cases is equipped with a conglomerate of interrelated systems and components that need to be properly inspected, maintained, and tested to ensure that the tunnel is kept open and performs reliably as designed. A preventive maintenance plan that considers future upgrading of systems should be developed prior to initial construction to ensure that tunnel operators are aware of those needs. Decision makers can then provide the necessary staffing and capital expenditure budget to ensure the continued viability of the tunnel and its systems.

The implementation strategy includes reaching out to owners of existing and new tunnels, describing the importance of planning for future tunnel expenses and the retention of well qualified personnel.

Specific activities will include presentations, webinars, articles, and proposed draft specifications. Recommendations on proposed guidance for tunnel design specifications to address this issue will be provided to the AASHTO Technical Committee for Tunnels, T-20.

### 7. Share existing technical knowledge within the industry to design a tunnel

Technical knowledge that exists within the industry should be shared with tunnel owners to provide them with a range of practical tunnel design options. This knowledge base would include domestic and international tunnel scan information, past project designs, construction practices, emergency response best practices, and subject matter experts. Value engineering can improve technology transfer with limited owner experience in tunnel systems (e.g., Value Engineering/Accelerated Construction Technology Transfer).

Design documents, including calculations and as-built documents, should be filed electronically, be easily retrievable by the controlling owner, and be appropriately backed-up (e.g., on microfilm).

Recognizing the security concerns of tunnel owners, the scan team believes that actual details and best practices used in tunnels should be shared with prospective and existing tunnel owners without identifying the specific facilities where these details and practices are used.

#### *Implementation Strategy*

The implementation strategy for sharing existing technical knowledge within the industry to design a tunnel will include research, technical presentations, workshops, and coordination with multiple agencies and tunnel owners. Strategies developed for implementation will include the structural design specification needs identified in this scan.

Strategies for design of roadway tunnels will include developing guidance for site specific design criteria and construction methods. The implementation strategy includes reaching out to owners of existing and new tunnels, describing the importance of sharing technical knowledge within the industry when designing a tunnel. Specific activities will include presentations, webinars, articles, and proposed draft design specifications. Recommendations on proposed guidance for the tunnel design specifications to address this issue will be provided to the AASHTO Technical Committee for Tunnels, T-20.

### 8. Provide education and training in tunnel design and construction

The scan team findings support training and development for owner agencies. Currently, few civil engineering programs in the U.S. offer a graduate course in tunneling, and it is likely that most civil engineers are not exposed to tunneling. Many DOTs do not have tunnels in their transportation systems; others built their last tunnel 20 to 30 years ago and, therefore, the in-house expertise is either nonexistent or out of date. Information gathered through host presentations, the desk scan, and discussions indicates that the number, magnitude, and complexity of tunneling projects will increase in the next few years. However, the current offering of short courses allows engineers to acquire only tunnel project nomenclature, not the required working knowledge.

Highway tunnel owners and the FHWA should provide their engineers with access to education and training on tunnels that is available through academia and industry. This involvement would also help direct academic research on tunneling. Reputable international online courses and certificates on tunneling would allow engineers to acquire up-to-date information and working knowledge in tunnel design and construction.

### *Implementation Strategy*

Currently, owner agencies are considering, designing, or managing the construction of road tunnels. Some of these projects are exceedingly demanding from the design and management viewpoints. In order for owner agencies' engineers to acquire working knowledge and education in tunneling, first they must have access to a database of available education and training venues on tunnels. Owners and engineers also must know where to acquire the funds to allocate to the current and projected needs for education and training in tunnels. At the same time, a nationwide recommendation on minimum education and training requirements would help owner agencies and engineers make the case for this effort.

## Implementation Plan Research

IImplementation strategies include several research proposals that ranged from a synthesis level of funding up to $50,000 (NCHRP 20-05), to focused efforts estimated under $100,000 (NCHRP 20-07), to full NCHRP project proposals. The scan team developed a list of recommended research topics that was prioritized by the AASHTO Technical Committee for Tunnels, T-20, with input from the TRB AFF60.

The prioritized research was partitioned into six categories. A brief summary of each category follows.

### *Category 1: Design and Construction*

This research involves developing LRFD specifications for the design and construction of roadway tunnels. Research topics for this category were developed with the intent to survey and gather comprehensive tunnel design and construction guidelines, best practices, and specifications. Research will be implemented through updates to the AASHTO *Technical Manual for Design and Construction of Road Tunnels – Civil Elements*[40] and various other tunnel related guidance and specifications.

### *Category 2: Maintenance*

The research involves soliciting information through surveys, desktop searches, and other means to gather information related to tunnel maintenance and inspection access. Access issues that could have been improved during the preliminary engineering or design phase will be identified. The information gathered will also serve as a source for developing guidelines for a comprehensive preventive maintenance plan for tunnel owners and operators.

### *Category 3: Incident Response*

[40] *Technical Manual for Design and Construction of Road Tunnels – Civil Elements,* AASHTO, August 2010

The research recommended for this category will start with a synthesis of actual tunnel fires and related human behavior. The focus will expand to include smoke ventilation and fire mitigation. The intent is for this research category to lead to the development of guidance for emergency response planning and incident response practices. The implementation will likely come with guidance developed for incident response with consideration given to human behavior.

### *Category 4: Operations*

The intent of this research category is to help tunnel owners develop a site-specific operations manual (guidance). Initial research should focus on establishing and maintaining target levels of condition, system reliability, and performance for roadway tunnel operations. A synthesis of best practices for tunnel operations, video surveillance, and communication systems will ultimately be the research focus areas. Implementation of the research is expected to come through a well developed operations manual.

### *Category 5: Procurement Methods*

The research will focus on establishing guidance and best practices for procurement methods for the design and construction of roadway tunnels. The expectation will be to develop comprehensive tunnel contracting guidelines.

### *Category 6: Training*

Both education and training on tunnel design, construction, and operation are needed. The initial focus will be to develop an international synthesis of education and training as it relates to roadway tunnels. This research is expected to establish current and projected needs for training and education for tunnel owners. Topics will include employee development, retention, and other resource and staffing needs-.

## Process for Following Up on the Status of Implementation Actions

The process that will be used to ensure timely completion of the actions under each strategy is including a discussion of the scan team implementation plan on the agenda of each AASHTO T-20 meeting, in cooperation with FHWA and the TRB AFF60. The implementation activities will be included as part of the T-20 Strategic Plan.

Appendix A:

# Amplifying Questions

Note: Below is a listing of the Amplifying Questions (AQs) as sent to the host agencies. The information in the body of the report is a compilation of host responses to the AQs prior to the scan, and presentations and discussions during the scan. It follows a logical order that differs from the order shown below.

## Topic 1: Specialized technologies currently used for existing and new US roadway tunnel design, construction, maintenance, inspection, and operations.

### Amplifying Questions:

**1.1 Design**

1.1.1 Have you used or considered specialized technologies for tunnel lighting luminance?

1.1.2 Have you used or considered specialized technologies for tunnel air quality / opacity air quality? If so:

1.1.2.1 What requirements do you have related to the air quality either in the tunnel or emanating from the tunnel such as through the vent towers?

1.1.2.2 Do you have air sampling requirements and reporting requirements, and if so, who regulates this?

1.1.2.3 Do ventilation stacks have air scrubbers on them?

1.1.3 What waterproofing systems have you employed?

**1.2 Construction**

1.2.1 What types of tunnel construction technologies have you used? For example, have you used tunnel-boring machines (TBMs) on any recent projects, and if so, how did they perform?

1.2.2 Have you used or considered technologies that accelerate the construction of tunnels?

1.2.3 Were any precast elements used on any of your projects? What was their performance?

**1.3 Maintenance, Repair, and Rehabilitation**

1.3.1 Have you used or considered technologies that improve efficiency in the maintenance and reconstruction of tunnels?

1.3.2 Have you employed specialized technologies to address issues related to water leakage?

1.3.3 For rehabilitation, a recent trend in concrete liners is to use steel fiber reinforcement only instead of prefabricated mesh as reinforcement. What is your experience regarding surface corrosion of the fibers, fiber distribution in the concrete, and the testing requirements for fiber-reinforced concrete liners?

1.3.4 If you have a roadway slab over a plenum, have you had to partially or fully replace the roadway deck and supporting floor system? If so, what technology did you use? Also, did you close the tunnel or do it under traffic or with off-hour closures?

### 1.4 Inspection

1.4.1 Have you used or considered technologies that improve efficiency in the inspection of tunnels?

1.4.2 Are you using any electronic methods to document conditions and deficiencies during the inspection of your tunnels (e.g., NDT methods to determine the integrity and condition of the tunnel liner, roadway slab, etc.)? If so, what are the methods and how have they worked for you? Do you have any suggestions for improving the methods?

1.4.3 Has special accessing equipment been used to inspect your tunnels? What is the equipment, and how did it perform?

### 1.5 Operations

1.5.1 What technologies do you use for incident detection, speed detection, intelligent transportation systems, smoke detection, backup power systems, and automated incident response? Explain their effectiveness and how the collected data are utilized to make operational adjustments.

1.5.2 What type of software product do you use for integrated and automated controls, (e.g., DYNAC, etc.)?

1.5.3 What technologies are you using to detect and prevent hazardous cargo from entering the tunnel?

1.5.4 Have you achieved cost efficiencies for utilities, (e.g., electric, lighting, water, etc.)?

### 1.6 General

1.6.1 Are you considering other, more advanced, technologies for use in existing and new tunnels? If so, please elaborate, including how you see these new technologies advancing "state of the practice" for tunnel owners.

1.6.2 Describe any specialized technology applications for existing and new tunnels that you would recommend but which are not included in the questions above.

## Topic 2: Standards, guidance, and "best practices" for existing and new roadway tunnels in the United States.

### Amplifying Questions:

**2.1 Design**

2.1.1 What design and other standards do you commonly use for new and existing roadway tunnels, e.g., NFPA 502, AASHTO, others?

2.1.2 What is your rationale for choosing certain parameters for your tunnel projects (e.g., reasons for choosing one alignment over another or for choosing a certain construction method over another)?

2.1.3 How was the clearance envelope for design decided (e.g., 14.0 feet too low because too many strikes happen)?

2.1.4 What seismic design criteria have you used for the design of your tunnels? For example, do you use 2500/100 dual level performance evaluation or single 1000-year event?

2.1.5 Strain limits due to seismic loading for a 2500-year event are 0.004 for concrete and 0.006 for steel reinforcing bar. For a 100-year event, the strain limits are 0.001 for concrete and 0.002 for steel reinforcing bar. Given the design meets the above noted strains, what is the correlation of strains to the mechanism that would cause collapse of the liner?

2.1.6 For a 100-year event, the strain limits are 0.001 for concrete and 0.002 for steel reinforcing bar. What correlation exists for acceptable damage and acceptable rates of leakage?

2.1.7 What seismic and other criteria do you use for portals and approach structures versus the main body?

2.1.8 What is your tunnel life expectancy (e.g., 100 to 150 years with engineering analysis for durability and longevity or AASHTO's 75-year service life-cycle?

2.1.9 What do you do when you encounter poor soils, (e.g., liquefiable soils)?

2.1.10 How are maintenance considerations worked into the design elements of a tunnel (e.g., washing, catwalks, railings, expansion joints, trench drains, lighting, exposed conduits, loop detectors, remote terminal units, and overhead signage/variable-message signs)?

**2.2 Construction**

2.2.1 What are some of the construction methods used on recent projects and why were they a best practice for your project? For example, in the case of the North Shore Connector project (Port Authority of Allegheny County –owner), the following were used: jet grouting, replacing a pile supported foundation for a highway bridge with a caisson/post-tensioned slab foundation, O-cell testing of the caissons, special contingency plan for traffic if the load transfer of the highway bridge failed.

2.2.2 Are you satisfied with the tunnel-boring machine (TBM) manufacturer support during construction? What are TBM maintenance challenges

## 2.3 Maintenance, Repair and Rehabilitation

2.3.1 What are the ages of your tunnels, and what maintenance issues do you encounter on a regular basis that can be attributed to the age of your tunnels?

2.3.2 Have the maintenance strategies that you employ been successful in decreasing the age-related maintenance issues? Are they keeping them in check or are the maintenance issues, money and resources increasing regardless of the maintenance effort?

2.3.3 How do you define "good repair" as it relates to your tunnel and tunnel systems (e.g., electrical, mechanical, lighting, communication, and emergency response)? Do you defer maintenance due to budget or other issues and, if so, how do you determine what is and is not to be deferred?

2.3.4 What is the biggest maintenance problem in your tunnels?

2.3.5 Have you completed any significant repairs or rehabilitation to concrete lined tunnels (e.g., linear replacement)? If so, what types of repair materials were used? Did you close the tunnel or did you do it under traffic or with off hour closures?

2.3.6 What type of ventilation systems do you have? Do you have supply plenums below the roadway and exhaust plenums above the roadway?

2.3.7 How does your agency handle the maintenance of devices (i.e., fire alarm pull stations, exit lights, and emergency strobe lights) with reference to the tunnel environment and tunnel washing?

2.3.8 Do you require that your tunnel be washed regularly?

2.3.9 How do you handle the workforce for maintenance activities (e.g., with in-house forces, outside on-call contractors, or dedicated contractors)? What types of on-call contracts do you have and how are their operations addressed through their contract?

2.3.10 What mechanism do you use to maintain, debug, and troubleshoot operation software systems (i.e., maintenance contract, in-house, or other)?

2.3.11 Do you have limitations on when tunnel maintenance can occur (e.g., time of day, seasonal, etc.)?

2.3.12 Do you have sufficient maintenance yard facilities to operate urban tunnel system(s)?

2.3.13 What routine maintenance, repair, and rehabilitation activities are you doing now that you would consider a best practice for other states to follow (e.g., methods of cleaning, cycles for preventive maintenance activities for mechanical/ electrical equipment, etc.)?

## 2.4 Inspection

2.4.1 Do you have separate inspection frequencies for each system (e.g., structural, electrical, mechanical, and communications) or system subcomponent? If so, what are the frequencies and how did you determine them?

2.4.2 How do you record and keep track of tunnel inspections, including deficiencies?

2.4.3 What manuals have you used to develop your tunnel inspection program?

2.4.4 Do you divide your tunnel into segments for inspection and reporting purposes? If so, how do you do it?

2.4.5 What procedures do you use to inspect rock tunnels with no lining?

2.4.6 Do you have limitations on when tunnel inspection can occur (e.g., time of day, seasonal, etc.)?

## 2.5 Operations

2.5.1 Are your operation controls for traffic and support facilities integrated using a central computer system and software? If so, which systems are integrated and which are stand-alone systems?

2.5.2 What measures are you taking to reduce the operating costs of your tunnels?

2.5.3 Do you do periodic trials of your emergency response systems (e.g., fire suppression, fire identification, communication, ventilation system performance, etc.)? What are the frequencies of these trials? What agencies have participated? Are reports available?

2.5.4 Do you have in place a procedure to keep records of fire incidents in the tunnel?

2.5.5 What mechanisms have you deployed to ensure that a fire in the tunnel can be contained to levels that do not pose hazards to the tunnel structures and operating systems, and limit the public's exposure to excessive heat, smoke, and carbon monoxide levels?

2.5.6 What is your procedure for communicating with local fire, emergency medical services, and police during an emergency, e.g., to what extent do you utilize interoperable communication systems in the tunnels among first responders and life-safety agencies?

2.5.7 What are the systems and protocols that you utilize to provide information to the public regarding emergency conditions in the tunnel and the forms of egress to use should an evacuation be necessary?

## 2.6 General

2.6.1 AASHTO T-20 Tunnel Definition:

"*Tunnels are defined as enclosed roadways with vehicle access that is restricted to portals regardless of type of structure or method of construction. Tunnels do not include highway bridges, railroad bridges or other bridges over a roadway. Tunnels are structures that require special design considerations that may include lighting, ventilation, fire protection systems, and emergency egress capacity based on the owner's determination.*"

The above tunnel definition was adopted by Resolution at the 2008 AASHTO Highway Subcommittee on Bridges and Structures (SCOBS) Annual Meeting. Does the AASHTO definition of a tunnel work for you? What changes would you recommend?

2.6.2 Tunnel Manual – 2009 ballot:

*The Technical Manual for Design and Construction of Road Tunnels - Civil Elements* ballot item was voted on and passed at the AASHTO Highway Subcommittee on Bridges and Structures (SCOBS) annual meeting in early July 2009. The manual will be published as an AASHTO publication and should be available in 2010. The on-line version submitted for ballot is available at the following website:
http://www.fhwa.dot.gov/bridge/tunnel/pubs/nhi09010/tunnel_manual.pdf
Please feel free to comment on the manual contents and future additions needed from your perspective.

2.6.3 Are you using a Tunnel Management System (TMS) to keep track of the condition, inspection, repair, and funds needed for your tunnels (e.g., the FHWA TMS that consists of inspection and maintenance manuals and database software)?

2.6.4 Describe any standards, guidance, and "best practices" for existing and new tunnels that you would recommend but which are not included in the questions above.

## Topic 3: Current criteria used by owners and states to identify tunnels in their inventory.

### Amplifying Questions:

3.1 How many tunnels do you have in your inventory?

3.2 How do you define a tunnel in your agency? Is any consideration given to length, type of construction, ventilation, or lighting in making your definition?

3.3 How do you differentiate between wide bridges over highways and short tunnels?

3.4 How do you inventory tunnels in your state (i.e., structure/tunnel number)? What is the basis?

3.5 How do you inventory the geometric characteristics of the tunnel (e.g., clearances, roadway widths, plenum sizes, etc.)?

3.6 Are the geometric data inventoried similar to the National Bridge Inspection Standards (NBIS) or are they different?

3.7 Do you use a Linear Referencing System to inventory tunnel segments, systems, call boxes, exits, etc., and if so, what do you use (e.g., mile points or survey stations)?

3.8 How do you inventory tunnel ramps and other changes in the tunnel cross section as they relate to the change in structure type, geometry, changes in plenum type, etc.?

3.9 Are portals, inclines and boat sections that lead to the tunnel itself inventoried as part of the tunnel or do you inventory them as separate structures?

Appendix B:

# Recent and Ongoing Research

Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspections, NCHRP 20-07/Task 261

Design Fires in Road Tunnels, NCHRP Project 20-05, Synthesis Topic 41-05

Tunnel Operations, Maintenance, Inspection and Evaluation (TOMIE) Manual, FHWA DTFH61-07-D 00004

High Speed Nondestructive Testing Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings, SHRP2 R06(G)

Recommended AASHTO LRFD Tunnel Design and Construction Specifications, NCHRP 12-89, FY 2011, ongoing

Guidelines for a Comprehensive Preventive Maintenance Plan for Tunnel Owners and Operators, pending

## Appendix C:

# Scan Itinerary

| Day, 2009 Date | Location | Activities |
|---|---|---|
| Monday, August 31 | Boston, Massachusetts | Meetings with Massachusetts Turnpike Authority (now MassDOT); Drive-through Tour of Prudential, I-90 Connector, Ted Williams, Sumner, Callahan, O'Neill, and Cana Tunnels; Tour of Operations Control Center; Tunnel Night Tour |
| Tuesday, September 1 | Boston, Massachusetts | Meeting with Massachusetts Turnpike Authority; Pennsylvania DOT webinar |
| Wednesday, September 2 | Newark, New Jersey | Meeting with Port Authority of New York & New Jersey |
| Thursday, September 3 | Hampton, Virginia | District of Columbia DOT Webinar; Meeting with Virginia DOT; Tour of Hampton Roads Bridge-Tunnel |
| Friday, September 4 | Cape Charles, Virginia | Meeting the Chesapeake Bay Bridge and Tunnel (CBBT) District; Tour of CBBT |
| Monday, September 14 | Denver, Colorado | Meetings with CDOT; Tours of Hanging Lake Tunnel and Eisenhower/Johnson Memorial Tunnel |
| Tuesday, September 15 | Seattle, Washington | Tours of Sound Transit Light Rail and Bus Tunnels, I-90 Tunnels (Mt. Baker and Mercer Island), and Battery Street Tunnel |
| Wednesday, September 16 | Seattle, Washington | Meetings with WSDOT, Seattle Fire Department, and Sound Transit; Alaska DOT webinar |
| Thursday, September 17 | San Francisco, California | Meeting with Caltrans; Tours of Caldecott Tunnel, Posey and Webster Street Tunnels, and Caltrans District 4 Traffic Management Center |
| Friday, September 18 | San Francisco, California | Meeting with Caltrans; Tour of Devil's Slide Tunnel |

## Appendix D:

# Host Agency Contacts

### Alaska Department of Transportation and Public Facilities (AKDOT&PF)

**Thomas J. Dougherty**, P.E. (primary contact)
Construction Group Chief, Central Region
Alaska Department of Transportation and Public Facilities
PO Box 196900
Anchorage, Alaska 99519-6900
Phone: (907) 269-0450
E-mail: thomas.dougherty@alaska.gov

### California Department of Transportation (Caltrans)

**Barton J. Newton**, P.E. (primary contact)
State Bridge Engineer
Deputy Division Chief, Structure Policy & Innovation
Division of Engineering Services
California Department of Transportation
P.O. Box 168041
1801 30th Street, MS 9-2/7J
Sacramento, CA 95816
Phone: (916) 227-8728
E-mail: barton_newton@dot.ca.gov

**Moe Amini**, P.E.
Senior Bridge Engineer
California Department of Transportation
Division of Engineering Services – Structure Design
Office of Structure Contract Management
1801 30th Street, MS 9-5/6G
Sacramento, CA 95816
Phone: (916) 227-4485
E-mail: moe_amini@dot.ca.gov

**Randy R. Anderson**, P.E.
Senior Bridge Engineer
California Department of Transportation
Division of Engineering Services – Structure Design
Office of Structure Contract Management
1801 30th Street, MS 9-5/6G
Sacramento, CA 95816
Phone: (916) 227-4488
E-mail: randy_anderson@dot.ca.gov

**Edward Coppin**
Supervisor
Caldecott Tunnels, Unit 04-798
California Department of Transportation
District 04 – Specialty Region
Tunnels & Tubes
420 Caldecott lane
West Portal Building
Oakland, CA 94618
Phone: (510) 286-0315
E-mail: edward.coppin@dot.ca.gov

**Richard S. Newell**
Senior Mechanical Engineer
California Department of Transportation
Division of Engineering Services – Structure Design
Office of Electrical, Mechanical, Water and Wastewater Engineering
1801 30th Street, MS 9-3/11H
Sacramento, CA 95816
Phone: (916) 227-8542
E-mail: rich_newell@dot.ca.gov

**Anthony Traina**
Senior Bridge Engineer
Quality Management Program Manager
California Department of Transportation
Structure Maintenance and Investigations
1801 30th Street
Sacramento, CA 95816
Phone: (916) 227-6994
E-mail: Anthony.traina@dot.ca.gov

## Chesapeake Bay Bridge and Tunnel District (CBBT District)

**Robert E. Johnson**, P.E. (primary contact)
Director of Maintenance
Chesapeake Bay Bridge and Tunnel District
32386 Lankford Highway
Cape Charles, VA 23310
Phone: (757) 331-2960
E-mail: rjohnson@cbbt.com

**Timothy R. Holloway**
Assistance Director of Maintenance
Chesapeake Bay Bridge and Tunnel District
32386 Lankford Highway
Cape Charles, VA 23310
Phone: (757) 331-2960
E-mail: tholloway@cbbt.com

**Michael A. Wells**
Electrical / Mechanical Superintendent
Chesapeake Bay Bridge and Tunnel District
32386 Lankford Highway
Cape Charles, VA 23310
Phone: (757) 331-8970
E-mail: mwells@cbbt.com

## Colorado Department of Transportation (CDOT)

**Pamela Hutton**, P.E. (primary contact)
Chief Engineer
Colorado Department of Transportation
4201 E. Arkansas Ave.
Denver, CO 80222
Phone: 303-757-9206
E-mail: pamela.hutton@dot.state.co.us

**Anthony DeVito**, P.E. (secondary contact)
Regional Transportation Director
Colorado Department of Transportation
18500 E. Colfax Ave.
Aurora, CO 80011
Phone: 303-365-700
E-mail: anthony.devito@dot.state.co.us

**Resa Dennie**
Transportation Maintenance III
Colorado Department of Transportation
Region 3 – Maintenance Section 2
Hanging Lakes Tunnel
202 Centennial
Glenwood Springs, CO 81601
Phone: (970) 945-3840
E-mail: resa.dennie@dot.state.co.us

**Joseph T. Elsen**, P.E.
Program Engineer – East
Colorado Department of Transportation
Region 3 Engineering
202 Centennial Street
Glenwood Springs, CO 81601
Phone: (970) 384-3332
E-mail joseph.elsen@dot.state.co.us

**Mike Goolsby**
Deputy Maintenance Superintendent
Colorado Department of Transportation
Region 3 – Maintenance Section 2
606 South 9th Street
Grand Junction, CO 81501
Phone: (970) 683-6306
E-mail: michael.goolsby@dot.state.co.us

**Pat Hawkins**
IT Professional I
Colorado Department of Transportation
Region 3 – Maintenance Section 2
606 South 9th Street
Grand Junction, CO 81501
Phone: (970) 683-6323
E-mail: patrick.hawkins@dot.state.co.us

**Rod Henderson**
LTC OPS I, Sr. Tunnel Supervisor
Colorado Department of Transportation
Eisenhower Memorial Tunnel
P.O. Box 397
Idaho Springs, CO 80452
Phone: (303) 512-5735
E-mail: rodney.henderson@dot.state.co.us

**Thomas E. Hurst**
Transportation Maintenance III
Colorado Department of Transportation
Eisenhower/Johnson Memorial Tunnels
P.O. Box 397
Idaho Springs, CO 80452
Phone: (303) 512-5734
E-mail: thomas.e.hurst@dot.state.co.us

**Kenny L. Martinez**
LTC Operations I
Colorado Department of Transportation
Eisenhower/Johnson Memorial Tunnels
P.O. Box 397
Idaho Springs, CO 80452
Phone: (303) 512-5733
E-mail: kenny.l.martinez@dot.state.co.us

**Steven Quick**
LTC OPS 1
Colorado Department of Transportation
Region 3 – Maintenance Section 2
Hanging Lakes Tunnel
202 Centennial
Glenwood Springs, CO 81601
Phone: (970) 945-3843
E-mail: steven.quick@dot.state.co.us

**Greg W. Sullivan**
Transportation Maintenance III
Colorado Department of Transportation
Region 3 – Maintenance Section 2
Hanging Lakes Tunnel
202 Centennial
Glenwood Springs, CO 81601
Phone: (970) 945-3842
E-mail: greg.sullivan@dot.state.co.us

**John F. Wilson**
Transportation Maintenance Supervisor III
Colorado Department of Transportation
Eisenhower/Johnson Memorial Tunnels
P.O. Box 397
Idaho Springs, CO 80452
Phone: (303) 512-5730
E-mail: john.wilson@dot.state.co.us

## District of Columbia Department of Transportation (DDOT)

**Simon Rennie** (primary contact)
Project Manager, Infrastructure Administration
District of Columbia Department of Transportation
64 New York Ave., NE
Washington, DC 20002
Phone: (202) 671-4666
E-mail: simon.rennie@dc.gov

**Aaron Horton**
District of Columbia Department of Transportation
64 New York Ave., NE
Washington, DC 20002
Phone: (202) 671-4679
E-mail: aaron.horton@dc.gov

## Massachusetts Department of Transportation (MassDOT) (previously Massachusetts Turnpike Authority)

**Helmut Ernst**, P.E. (primary contact)
Chief Engineer
Massachusetts Turnpike Authority
10 Park Plaza, Suite 4160
Boston, MA 02116
Phone: (617) 519-6431
E-mail: helmut.ernst@masspike.com

**Lorenzo G. Parra** (secondary contact)
Director of Emergency Preparedness
Massachusetts Turnpike Authority
10 Park Plaza, Suite 4160
Boston, MA 02116
Phone: (617) 248-2945
E-mail: lorenzo.parra@masspike.com

**Mark Loiselle**
Health and Safety Coordinator
Massachusetts Turnpike Authority
668 South Avenue
Weston, MA 02493
Phone: (781) 431-5188
E-mail: mark.loiselle@masspike.com

**Major Michael C. Mucci**
Commanding Officer
Massachusetts State Police – Troup E
Massachusetts Turnpike Authority
50 Massport Haul Road
Boston, MA 02210-2002
Phone: (617) 946-3051
E-mail: michael.mucci@pol.state.ma.us

## Pennsylvania Department of Transportation (PennDOT)

**Tom Macioce**, P.E. (primary contact)
Chief Bridge Engineer
Pennsylvania DOT
400 North Street
Bureau of Design
Harrisburg, PA 17120
Phone: (717) 787-2881
E-mail: tmacioce@state.pa.us

## Port Authority of New York and New Jersey (PANY&NJ)

**Bernard Yostpille**, P.E. (primary contact)
Assistant Chief Structural Engineer
Engineering/Architecture Design Division
The Port Authority of NY & NJ
Engineering Department
Two Gateway Center, 16NE
Newark, NJ 07102
Phone: (973) 792-4545
E-mail: byostpil@panynj.gov

**Steve Wondoloski**, P.E. (secondary contact)
Principal Structural Engineer
Engineering/Architecture Design Division
The Port Authority of NY & NJ
Engineering Department
Two Gateway Center, 16NE
Newark, NJ 07102
Phone: (973) 792-4540
E-mail: swondolo@panynj.gov

**Walter Brusey**
Senior Geotechnical Engineer
Engineering/Architecture Design Division
The Port Authority of NY & NJ
Engineering Department
Two Gateway Center, 16NE
Newark, NJ 07102
Phone: (973) 792-7581
E-mail: wbrusey@panynj.gov

**Mitchell Aldea**, P.E.
Manager, Facility Condition Surveys Unit
Quality Assurance Division
The Port Authority of NY & NJ
Engineering Department
3 Gateway Center, 3rd Floor
Newark, NJ 07102
Phone: (973) 792-3940
E-mail: maldea@panynj.gov

**John T. McConkey**, P.E. (primary contact)
Chief Electrical Engineer
Engineering/Architecture Design Division
The Port Authority of NY & NJ
Engineering Department
Two Gateway Center, 16SW
Newark, NJ 07102
Phone: (973) 792-4330
E-mail: jmcconke@panynj.gov

**Viorel Borza** (secondary contact)
Senior Electrical Engineer
Engineering/Architecture Design Division
The Port Authority of NY & NJ
Engineering Department
Two Gateway Center, 16SW
Newark, NJ 07102
Phone: (973) 792-4397
E-mail: vborza@panynj.gov

**Cheng Chang**, P.E.
Chief Mechanical Engineer
Engineering/Architecture Design Division
The Port Authority of NY & NJ
Engineering Department
Two Gateway Center, 14th Floor
Newark, NJ 07102
Phone: (973) 565-7630E-mail: cchang@panynj.gov

## Seattle Department of Transportation (Seattle DOT)

**Larry Finnick** (primary contact)
Mechanical and Electrical Supervisor
Seattle Department of Transportation
Roadway Structures
PO Box 34996
Seattle, WA 98124-4996
Phone: (206) 386-4268
E-mail: Larry.Finnick@seattle.gov

## Seattle Fire Department

**Deputy Chief Gary English** (primary contact)
Assistant Fire Marshal - Special Projects
Seattle Fire Department
220 Third Avenue South
Seattle, WA 98104
Phone: (206) 386-1453
E-mail: gary.english@seattle.gov

## Sound Transit

**Joseph P. Gildner**, P.E. (primary contact)
Deputy Director, Link Director's Office
Link Light Rail Department
Sound Transit – Union Station
401 S. Jackson St.
Seattle, WA 98104-2826
Phone: (206) 689-3350
E-mail: gildnerj@soundtransit.org

**Isam Awad**, Ph.D., P.E.
Senior Civil Engineer – Structural
Link Light Rail Department
Sound Transit – Union Station
401 S. Jackson St.
Seattle, WA 98104-2826
Phone: (206) 689-3399
E-mail: awadi@soundtransit.org

## Virginia Department of Transportation (VDOT)

**Prasad L. Nallapaneni**, P.E. (primary contact)
Bridge Maintenance Program Manager
Virginia DOT
Structure and Bridge Division
1401 E. Broad St.
Richmond, VA 23219
Phone: (804) 371-2770
E-mail: Prasad.Nallapaneni@VDOT.Virginia.gov

**Gregory M. Nataluk**, P.E.
Area Operations Engineer
Virginia DOT
204 National Avenue
Hampton, VA 23663
Phone: (757) 727-4875
E-mail: Gregory.Nataluk@VDOT.Virginia.gov

**Richard E. Thompson**, P.E.
Bridge Management Engineer Senior
Virginia DOT
Structure and Bridge Division
1401 E. Broad St.
Richmond, VA 23219
Phone: (804) 786-1024
E-mail: Richard.Thompson@VDOT.Virginia.gov

**Alton M. Yates**
Computer Systems Engineer
Virginia DOT
Hampton Roads Smart Traffic Center
P.O. Box 3447
Hampton, VA 23663
Phone: (757) 727-4813
E-mail: Alton.Yates@VDOT.Virginia.gov

## Washington State Department of Transportation (WSDOT)

**Jugesh Kapur**, P.E., S.E. (primary contact)
State Bridge and Structures Engineer
Washington State DOT
Bridge and Structures Office
7345 Linderson Way SW
Tumwater, WA 98501
Phone: (360) 705-7207
E-mail: kapurju@wsdot.wa.gov

**Tom Badger,** L.E.G., L.H.G., P.E.
Assistant Chief Engineering Geologist
Geotechnical Division
Washington State DOT
Environmental and Engineering Programs
State Materials Laboratory
1655 South Second
Tumwater, WA 98512
Phone: (360) 709-5461
E-mail: badgert@wsdot.wa.gov

**David Dinges**
Chief Bridge Inspector
Washington State DOT
Northwest Region
10833 Northup Way NE
Bellevue, WA 98004
Phone: (425) 739-3707
E-mail: dingesd@wsdot.wa.gov

**Susan L. Everett**
Alaskan Way Viaduct Program Design Manager
Washington State DOT
Urban Corridors Office
401 2nd Avenue South, Ste. 400, TB85-95
Seattle, WA 98104
Phone: (206) 464-1215
E-mail: everetts@wsdot.wa.gov

**Linea Laird**, P.E.
Director of Design-Build
Alaskan Way Viaduct and Seawall Replacement Program
Washington State DOT
Urban Corridors Office
999 Third Avenue, Ste. 2424
Seattle, WA 98104
Phone: (206) 267-6834
E-mail: lairdl@wsdot.wa.gov

**Timothy M. Moore**, P.E., S.E.
Structural Design Mega Project Manager
Washington State DOT
Bridge and Structures Office
7345 Linderson Way SW
Tumwater, WA 98501
Phone: (360) 705-7163
E-mail: mooret@wsdot.wa.gov

**Eric Sniezak**, P.E.
Senior Lead Bridge Inspection Engineer
Environmental and Engineering Programs
Washington State DOT
Bridge and Structures Office
7345 Linderson Way SW
Tumwater, WA 98501
Phone: (360) 570-2568
E-mail: sniezake@wsdot.wa.gov

**Scott Vanantwerp**
Tunnel Supervisor
Mt. Baker/Mercer Island Tunnel Maintenance
Washington State DOT
Northwest Region – Area 5 Maintenance
10833 Northup Way NE
Bellevue, WA 98004
Phone: (206) 440-5206
E-mail: vanantj@wsdot.wa.gov

**John H. White**, P.E.
Director of Engineering and Administration
Alaskan Way Viaduct and Seawall Replacement Program
Washington State DOT
Urban Corridors Office
999 Third Avenue, Ste. 2424
Seattle, WA 98104
Phone: (206) 382-5270
E-mail: whitejh@wsdot.wa.gov

# Appendix E:

# Tunnel Inventories

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| California | Devil's Slide | [a] | 4265 | 2 | 1 | 14,500 | 2.7 | Longitudinal |
| | Caldecott Tunnel #4 | [a] | 3399 | 1 | 2 | 29,500 | 2.3 | Longitudinal |
| | Doyle Drive S/B Battery | [a] | 1034 | 1 | 5 | 39,500 | 1.3 | Longitudinal |
| | Randolph Collier Tunnel | 1963 | 1886 | 1 | 2 | 2,700 | 12 | Semi transverse, One portalexhaust only |
| | Sunrise OnRamp | 2006 | 627 | 1 | 1 | – | – | Longitudinal |
| | Caldecott Tunnel #1 | 1937 | 3616 | 1 | 2 | 48,100 | 2.3 | Full transverse Two portals |
| | Caldecott Tunnel #2 | 1937 | 3610 | 1 | 2 | 48,100 | 2.3 | Full transverse Two portals |
| | Caldecott Tunnel #3 | 1965 | 3371 | 1 | 2 | 58,900 | 2.3 | Full transverse One portal |
| | Posey Tube | 1927 | 3545 | 1 | 2 | 29,300 | 2.4 | Full transverse Two portals |
| | Webster Tube | 1963 | 3350 | 1 | 2 | 29,900 | 2.4 | Full transverse Two portals |
| | W92S280 Conn UC | 1973 | 900 | 1 | 2 | 12,500 | 1.7 | Mid tunnel single point extraction |
| | Angeles Crest Tunnel #2 | 1950 | 434 | 1 | 2 | 395 | 2 | None, CO monitoring |
| | Angeles Crest Tunnel #1 | 1950 | 589 | 1 | 2 | 395 | 2 | None, CO monitoring |
| | Arch Rock Tunnel | 1937 | 239 | 1 | 2 | 1550 | 5 | None, CO monitoring |

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| | Bay Point UC | 1976 | 594 | 1 | 2 | 50 | 0 | None, CO monitoring |
| | Elephant Butte Tunnel | 1937 | 1086 | 1 | 2 | 1375 | 15 | None, CO monitoring |
| | Figueroa Street Tunnel | 1931 | 370 | 1 | 2 | 189,000 | 2 | None, CO monitoring |
| | Figueroa Street Tunnel | 1931 | 119 | 1 | 2 | 87350 | 1 | None, CO monitoring |
| | Figueroa Street Tunnel | 1936 | 690 | 1 | 2 | 87350 | 1 | None, CO monitoring |
| | Figueroa Street Tunnel | 1931 | 422 | 1 | 2 | 87350 | 1 | None, CO monitoring |
| | Fort Chronkhite Tunnel | 1918 | 2460 | 1 | 2 | 5000 | 3 | None, CO monitoring |
| | Gaviota Gorge Tunnel | 1953 | 384 | 1 | 2 | 11750 | 12 | None, CO monitoring |
| | Grizzly Dome Tunnel | 1936 | 357 | 1 | 2 | 1375 | 15 | None, CO monitoring |
| | McClure Tunnel | 1935 | 366 | 1 | 2 | 58000 | 2 | None, CO monitoring |
| | Middle Matilija Tunnel | 1931 | 120 | 1 | 2 | 650 | 4 | None, CO monitoring |
| | Middle Matilija Tunnel | 1931 | 156 | 1 | 2 | 650 | 4 | None, CO monitoring |
| | Presidio Tunnel | 1938 | 792 | 1 | 2 | 69000 | 3 | None, CO monitoring |
| | South Matilija Tunnel | 1931 | 188 | 1 | 2 | 650 | 4 | None, CO monitoring |
| | Waldo Tunnel | 1937 | 914 | 1 | 2 | 108000 | 2 | None, CO monitoring |

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| | Waldo Tunnel | 1954 | 914 | 1 | 2 | 108000 | 2 | None, CO monitoring |
| Colorado | B-15-E | 1929 | 95 | 1 | 2 | 900 | 10 | Natural |
| | D-15-AS | 1953 | 350 | 1 | 2 | 7,300 | 3 | Natural |
| | F-07-Q | 1965 | 1,044 | 1 | 2 | 16,200 | 15 | Natural |
| | F-07-R | 1965 | 1,045 | 1 | 2 | 16,200 | 15 | Natural |
| | F-08-AP | 1992 | 4,000 | 1 | 2 | 8,000 | 15 | Semitransverse |
| | F-08-AQ | 1992 | 4,000 | 1 | 2 | 8,000 | 15 | Semitransverse |
| | F-08-AT | 1989 | 582 | 1 | 2 | 8,000 | 15 | Natural |
| | F-13-X | 1979 | 8,959 | 1 | 2 | 28,800 | 10 | Fulltransverse |
| | F-13-Y | 1973 | 8,941 | 1 | 2 | 28,800 | 10 | Fulltransverse |
| | F-15-AW | 1957 | 769 | 1 | 2 | 13,300 | 3 | Natural |
| | F-15-AX | 1941 | 1,068 | 1 | 2 | 13,300 | 3 | Natural |
| | F-15-AY | 1951 | 883 | 1 | 2 | 13,300 | 3 | Natural |
| | F-15-BN | 1961 | 725 | 1 | 2 | 41,200 | 8 | Natural |
| | F-15-BO | 1961 | 665 | 1 | 2 | 41,200 | 8 | Natural |
| | F-15-X | 1939 | 588 | 1 | 2 | = | 4 | Natural |
| | F-15-Y | 1939 | 411 | 1 | 2 | 4,900 | 4 | Natural |
| | H-03-BT | 1986 | 625 | 1 | 2 | 17,400 | 14 | Natural |
| | H-03-BU | 1986 | 615 | 1 | 2 | 17,400 | 14 | Natural |
| | L-06-P | 1942 | 165 | 1 | 2 | 2,200 | 11 | Natural |
| | N-09-F | 2002 | 1,026 | 1 | 2 | 2,700 | 12 | Natural |
| Chaffee County, Colorado | CHA371-02.50 | 1887 | 40 | 1 | 1 | 220 | 4 | Natural |
| | CHA371-02.52 | 1887 | 115 | 1 | 1 | 220 | 4 | Natural |

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| | CHA371-02.55 | 1887 | 165 | 1 | 1 | 220 | 4 | Natural |
| | CHA371-02.80 | 1887 | 65 | 1 | 2 | 220 | 4 | Natural |
| Colorado Springs (Mtn Park), Colorado | CSG-C.40-05.85T | 1901 | 16 | 1 | 1 | 300 | 0 | Natural |
| | CSG-D.09-06.19T | 1901 | 15 | 1 | 1 | 300 | 0 | Natural |
| Denver (Mtn Park), Colorado | D-27-MP-220 | 1940 | 56 | 1 | 2 | 665 | 0 | Natural |
| Fremont County, Colorado | FRCO 67-317 | 1894 | 312 | 1 | 1 | 136 | 9 | Natural |
| | FRCO 67-318 | 1894 | 249 | 1 | 1 | 136 | 9 | Natural |
| Teller County, Colorado | TELL-8-TUN | 1900 | 243 | 1 | 1 | 36 | 0 | Natural |
| Massachusetts | Sumner | 1934 | 5,653 | 1 | 2 | 22,000 | 3 | Fully transverse |
| | Callahan | 1961 | 5,071 | 1 | 2 | 24,000 | 3 | Fully transverse |
| | Prudential | 1965 | 3,200 | 1 | 34 | 145,000 | 5 | Longitudinal |
| | CANA | 1989 | 1,000 | 2 | 3 | 60,000 | 4 | Fully transverse |
| | Ted Williams | 1995 | 8,100 | 2 | 2 | 80,000 | 5 | Fully transverse |
| | I-90 Connector | 2003 | 5,350 | 4 | 13 | 80,000 | 5 | Fully transverse, longitudinal for some ramps |
| | Thomas P. O'Neill (I-93) | 2003 | 8,400 | 2 | 45 | 200,000 | 4 | Fully transverse, longitudinal for some ramps |
| Pennsylvania | Layton | 1899 | 219 | 1 | 1 | 1,256 | 4 | Natural |
| | Stowe | 1909 | 492 | 2 | 2 | 6,599 | 1 | Natural |

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| | Liberty | 1926 | 5,889 | 2 | 4 | 41,826 | 9 | Fully transverse |
| | Fort Pitt | 1952NB 1957SB | 3,614 | 2 | 4 | 123,268 | 9 | Semi-transverse |
| | Squirrel Hill | 1955 | 4,225 | 2 | 4 | 70,494 | 9 | Semi-transverse |
| | Allegheny (WB) [b] | 1940 | 6,070 | 2 | 2 | 14,807 | 31 | Semi-transverse at portals |
| | Allegheny #2 (EB) [b] | 1965 | 6,070 | 2 | 2 | 15,577 | 31 | Semi-transverse at portals |
| | Tuscarora (EB) [b] | 1940 | 5,326 | 2 | 2 | 11,106 | 32 | Semi-transverse at portals |
| | Tuscarora #2 (WB) [b] | 1968 | 5,326 | 2 | 2 | 10,450 | 32 | Semi-transverse at portals |
| | Kittatinny (WB) [b] | 1940 | 4,727 | 2 | 2 | 10,582 | 31 | Semi-transverse at portals |
| | Kittatinny #2 (EB) [b] | 1968 | 4,727 | 2 | 2 | 11,230 | 31 | Semi-transverse at portals |
| | Blue (WB) [b] | 1940 | 4,339 | 2 | 2 | 10,582 | 31 | Semi-transverse at portals |
| | Blue #2 (EB) [b] | 1968 | 4,339 | 2 | 2 | 11,230 | 31 | Semi-transverse at portals |
| | Lehigh (NB) [b] | 1957 | 4,382 | 2 | 2 | 14,759 | 16 | Reversible semitransverse fans at portals |
| | Lehigh #2 (SB) [b] | 1991 | 4,382 | 2 | 2 | 15,038 | 16 | Longitudinal jet fans |
| Port Authority of NY&NJ | Holland | 1927 | 8,558N 8,371S | 2 | 2 | 94,300 | N/A | Fully transverse |

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| | Lincoln | 1937Ctr<br>1945N<br>1957S | 8,216Ctr<br>7,482N<br>8,006S | 3 | 2 | 108,000 | N/A | Fully transverse |
| | 41st Street Underpass | 1975 | 550 | 1 | 2 | N/A | 0 | Fully transverse |
| Virginia CBBT | Chesapeake Channel | 1964 | 5,423 | 1 | 2 | 9,50010,000 | 10 | Fully transverse |
| | Thimble Shoal | 1964 | 5,734 | 1 | 2 | 9,50010,000 | 10 | Fully transverse |
| Virginia DOT | Midtown Tunnel | 1962 | 4,200 | 1 | 2 | 35,410 | 18 | Full transverse |
| | Hampton Roads Bridge TunnelWBL | 1958 | 7,480 | 1 | 2 | 88,022 | 12 | Full transverse |
| | Hampton Roads Bridge TunnelEBL | 1974 | 7,315 | 1 | 2 | 88,022 | 12 | Full transverse |
| | Big Walker Mountain Tunnel | 1972 | 4,200 | 2 | 2 | 28,000 | 15 | Full transverse |
| | East River Mountain Tunnel | 1974 | 5,412 | 2 | 2 | 28,000 | 8 | Full transverse |
| | Downtown Tunnel (First)-WBL | 1952 | 3,350 | 1 | 2 | 91,793 | 10 | Semi transverse |
| | Downtown Tunnel (Second)-EBL | 1986 | 3,814 | 1 | 2 | 91,793 | 10 | Semi transverse |
| | NAS Runway #29 Underpass | 1977 | 662 | 2 | 2 | No data | No data | None |
| | Monitor-Merrimac Memorial Bridge Tunnel | 1992 | 4,860 | 2 | 2 | 55,857 | 15 | Full transverse |
| Washington | Tunnel (2/108) | 1937 | 184 | 1 | 2 | 3433 | 19 | None |
| | Convention Center (5/549cnc) | 1988 | 547 | 1 | 6 | 94985 | 6 | None |
| | Rimrock T (12/308) | 1936 | 577 | 1 | 2 | 3112 | 5 | None |

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| | Tunnel No 1 (14/128) | 1937 | 130 | 1 | 2 | 3084 | 5 | None |
| | Tunnel No 2 (14/129) | 1937 | 408 | 1 | 2 | 3084 | 5 | None |
| | Tunnel No 3 (14/130) | 1937 | 257 | 1 | 2 | 3084 | 5 | None |
| | Tunnel No 5 (14/134) | 1937 | 212 | 1 | 2 | 3112 | 5 | None |
| | Tunnel (14/215) | 1933 | 389 | 1 | 2 | 931 | 16 | None |
| | Lyle Tunnel (14/216) | 1933 | 233 | 1 | 2 | 1433 | 12 | None |
| | Tunnel (20/316) | 1962 | 625 | 1 | 2 | 3433 | 19 | None |
| | Tunnel (20/327) | 1962 | 88 | 1 | 2 | 1226 | 16 | None |
| | Martin L King Lid (90/22lid) | 1989 | 2,012 | 1 | 3 | 12209 | 6 | Longitudinal |
| | Mt Baker Ridge (90/24n) | 1989 | 1,476 | 2 | 4 | 58666 | 6 | Longitudinal |
| | Mt Baker Ridge (90/24s) | 1940 | 3,456 | 2 | 4 | 58666 | 6 | Longitudinal |
| | First Hill Lid (90/26lid) | 1989 | 2,873 | 2 | 3 | 116697 | 6 | Longitudinal |
| | Knapps Hill (97/359alt) | 1936 | 788 | 1 | 2 | 3948 | 11 | None |
| | Fort Columbia (101/3) | 1932 | 800 | 1 | 2 | 4440 | 20 | None |
| | Tunnel No 4 (14/133) | 1937 | 261 | 1 | 2 | 1564 | 8 | None |
| | Tunnel (123/106) | 1935 | 510 | 1 | 2 | 622 | 10 | None |
| | S Park Plaza UC (5/548PS) | 1976 | 77 | 1 | 2 | 1878 | 6 | None |
| | N Park Plaza UC (5/549PN) | 1976 | 289 | 1 | 2 | 1878 | 6 | None |
| | SCol Ramp W Plaza UC (5/548PW) | 1976 | 83 | 1 | 2 | 2433 | 6 | None |

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| | E-S Ramp (5/555E-S) | 1967 | 600 | 1 | 2 | 15605 | 5 | None |
| | N-W Ramp (5/555-NW) | 1963 | 888 | 1 | 2 | 15094 | 5 | None |
| | Roosevelt Way (522/15) | 1962 | 390 | 1 | 3 | 28146 | 4 | None |
| | 5th-Exp (5/546REV) | 1964 | 631 | 1 | 3 | 25153 | 5 | None |
| | N-W I-90 UC (405/35NW) | 1968 | 435 | 1 | 2 | 12565 | 5 | Single point extraction |
| | S-E I-90 UC (405/35S-E) | 1968 | 305 | 1 | 3 | 22843 | 5 | None |
| | BN UC (405/40W) | 1972 | 360 | 1 | 2 | 14656 | 6 | None |
| | S-E Ramp (5/568S-E) | 1962 | 662 | 1 | 2 | 17491 | 5 | None |
| | S-E Ramp (90/16S-E) | 1992 | 371 | 1 | 2 | 17400 | 5 | None |
| | N-W Ramp (90/33N-W) | 1989 | 1113 | 1 | 2 | 1020 | 5 | None |
| | REV E-S Ramp (90/33REV) | 1989 | 566 | 1 | 2 | 6000 | 5 | None |
| | E-S Ramp (90/33E-S) | 1992 | 280 | 1 | 2 | 2417 | 5 | None |
| | E-N Ramp (526/22E-N) | 1995 | 466 | 1 | 2 | 11423 | 5 | None |
| | ASARCO | 1912 | 325 | 1 | 2 | 2345 | 6 | None |
| | Vasa Park Road OCSE 35th P (90/55) | 1974 | 38 | 1 | 4 | 100136 | 6 | None |
| | BN UC (14/111) | 1978 | 180 | 1 | 2 | 4564 | 15 | None |
| | Exp (5/553R) | 1963 | 801 | 1 | 3 | 27084 | 6 | None |

| Owner | Tunnel name | Year built | Length (ft) | No. of tubes | Lanes/ tubes | ADT | % trucks | Ventilation type |
|---|---|---|---|---|---|---|---|---|
| | Lake Keechelus Snowshed (90/110N) | 1950 | 500 | 1 | 2 | 14237 | 18 | None |
| | Battery Street (99/541) | 1954 | 2140 | 1 | 2 | 54406 | 5 | Single point extraction |
| | RavennaS-Ramp (90/577E-S) | 1961 | 152 | 1 | 2 | 5814 | 5 | None |

[a] Under construction; will be in operation by 2013

[b] Owned by Pennsylvania Turnpike Commission, as reported by PennDOT.

Appendix F:

# Scan Team Contact Information

**Kevin Thompson,** P.E. – AASHTO Chair
State Bridge Engineer
California Dept. of Transportation
Div. Engr. Services, Structure Design
1801 30th Street
Sacramento, CA 95816 8041
Phone: (916) 227 8807
Fax: (916) 227 8149
E-mail: kevin.thompson@dot.ca.gov

**Jesus Rohena,** P.E. – FHWA Chair
Senior Tunnel Engineer
Federal Highway Administration
Office of Bridge Technology, HIBT 10
1200 New Jersey Avenue, S.E.
Washington, DC 20590
Phone: (202) 366 4593
Fax: (202) 366 3077
E-mail: jesus.rohena@dot.gov

**Alexander K. Bardow,** P.E.
Director of Bridges and Structures
Massachusetts Dept. of Transportation
10 Park Plaza, Suite 6430
Boston, MA 02116 3973
Phone: (617) 973 7571
Fax: (617) 973 7554
E-mail: alexander.bardow@state.ma.us

**Louis Ruzzi,** P.E.
District Bridge Engineer
Pennsylvania Dept. of Transportation
Engineering District 11 0
45 Thoms Run Road
Bridgeville, PA 15017
Phone: (412) 429 4893
Fax: (412) 429 5085
E-mail: lruzzi@state.pa.us

**Barry B. Brecto**, P.E.
Division Bridge Engineer
FHWA Washington State Division
711 S. Capitol Way, Suite 501
Olympia, WA 98501
Phone: (360) 753 9482
Fax: (360) 753 9889
E-mail: barry.brecto@dot.gov

**Michael G. Salamon**
Tunnel Superintendent
Colorado Dept. of Transportation
PO Box 397
Idaho Springs, CO 80453
Phone: (303) 512 5731
Fax: (303) 512 5799
E-mail: michael.salamon@dot.state.co.us

**Bijan Khaleghi,** Ph.D., P.E., S.E.
State Bridge Design Engineer
Washington State Dept. of Transportation
Bridge & Structures Office
PO Box 47340
Olympia, WA 98504 7340
Phone: (360) 705 7181
Fax: (360) 705 6814
E-mail: khalegb@wsdot.wa.gov

**Fulvio Tonon,** Ph.D., P.E.
Assistant Professor
The University of Texas at Austin
Department of Civil Engineering
1 University Station C1792
Austin, TX 78712 0280
Phone: (512) 475 8196
Fax: (512) 471 6548
E-mail: tonon@mail.utexas.edu

**Mary Lou Ralls, P.E.** – Report Facilitator
Principal
Ralls Newman, LLC
2906 Pinecrest Drive
Austin, TX 78757
Phone: (512) 422 9080
Fax: (512) 371 3778
Email: ralls newman@sbcglobal.net

# Appendix G:

# Scan Team Biographical Information

**KEVIN J. THOMPSON** *(AASHTO CO-CHAIR)* is currently the State Bridge Engineer for the California Department of Transportation. External responsibilities include AASHTO Vice Chair for the Highway Subcommittee on Bridges and Structures and California Board member for Western Bridge Engineers, Inc. Thompson also serves on the American Segmental Bridge Institute (ASBI) Executive Board. He is also the Deputy Division Chief for Structure Design in the Department's Division of Engineering Services. As Chief of Structure Design, Thompson directs the work of approximately 375 people in five structure design offices. In addition, he is ultimately responsible for the work of all structure design technical committees and specialists in the review, approval and maintenance of bridge design standards and guidance material. Thompson has worked for the California Department of Transportation for 26 years. During that time, he has held a variety of positions in bridge design, highway and structure construction, contract advertisement and award, and transportation management. The majority of his experience is in the area of bridge design. He received a Bachelors of Science degree in Civil Engineering from Arizona State University in 1983 and he is a licensed Professional Engineer in California.

**JESUS M. ROHENA** *(FHWA CO-CHAIR)* is the senior tunnel engineer for the FHWA Office of Bridge Technology in Washington, DC. Rohena is responsible for managing FHWA's Federal-aid tunnel program for all States, the District of Columbia, and Puerto Rico. He is leading the FHWA effort to develop National Tunnel Inspection Standards (NTIS). He has worked with FHWA in the field of tunnel engineering since 1990. Prior to 1990, Rohena worked on roadway design and construction projects for the Federal Lands. He served as the assistant tunnel engineer from 1990 to 2000. From 2000 to 2004 he moved to the FHWA Resource Center as the complex structures specialist, however he kept working closely with the senior tunnel engineer in all matters related to tunnels. In 2004, when the senior tunnel retired, Rohena was selected as the FHWA senior tunnel engineer. He has a bachelor's degree in civil engineering from the University of Puerto Rico and a master's degree in structural engineering from the George Washington University in Washington, DC. He is a licensed professional engineer in Virginia. He serves on the TRB Tunnels and Underground Structures Technical Committee, and is a member of the National Fire Protection Association (NFPA), the World Road Association (PIARC) Technical Committee C4 Road Tunnel Operation, and the International Tunneling Association (ITA). He serves as the FHWA liaison to the AASHTO Subcommittee T-20 on Tunnels.

**ALEXANDER K. BARDOW** is the Director of Bridges and Structures for the Massachusetts Highway Department. He has worked for the Massachusetts Highway Department Bridge Section in various positions since 1983. In 1995, Bardow was appointed Bridge Engineer, and, in March 2006, was promoted to the newly created position of Director of Bridges and Structures. In this position, he oversees the operations of the MassHighway Bridge Section, including the design of bridge and bridge preservation projects, and the inspection and load rating of bridges. In the wake of the July 2006 Big Dig tunnel ceiling collapse, Bardow was in charge of the design of the ceiling remediation project. He received both his BSCE and MSCE degrees from Massachusetts Institute of Technology (MIT) and is a Professional Engineer registered in Massachusetts. Bardow is a voting member of the AASHTO Subcommittee on Bridges and Structures (SCOBS) and serves on the following technical committees: Welding, of which he is the Chair; Timber, of which he is the Vice Chair; Seismic Design; and Tunnels. He is a member of the PCI New England Technical Committee and is a member of both American Society of Civil Engineers (ASCE) and the Boston Society of Civil Engineers Section (BSCES) of ASCE. He has served in several elected offices within BSCES, including as President for 2004–05.

**BARRY B. BRECTO** is the Division Bridge Engineer for the Washington Division of the Federal Highway Administration. In that capacity he has overseen the federal aid program for the design, construction, maintenance, and inspection of bridges and tunnels in Washington State over the past 19 years. Brecto has been involved with several major tunnels, such as the I 90 Mount Baker Ridge Tunnel, the Alaskan Way Viaduct replacement tunnel, the I 90 Mercer Island Lids, and Seattle's Battery Street Tunnel. Prior to his current position he was the Regional Structural Engineer for FHWA Region 10, with responsibilities in Washington, Oregon, Idaho, and Alaska. He is a member of FHWA's team to develop National Tunnel Inspection Standards and has participated in FHWA efforts to update bridge inspection standards, coding guides, and inspection manuals. He received his bachelor of science degree in Civil Engineering from Washington State University, and is a licensed Civil Engineer in the State of Oregon.

**BIJAN KHALEGHI** is the State Bridge Design Engineer with the Washington State Department of Transportation (WSDOT) Bridge and Structures Office. He received his Master and Doctor of Engineering degrees from the National Institute of Applied Sciences, Lyon, France. He is a member of many committees and task forces, including the American Association of State Highway and Transportation Officials (AASHTO) Technical Committees on Concrete Bridges T-10, Research T-11, Tunnels T-20, ASBI and PCI Bridge Technical Committees. Before his current position, Bijan was the Concrete Specialist for WSDOT Bridge and Structures office. Among his other responsibilities, Bijan is the designated structural engineer for the Alaskan Way Viaduct Tunnel project in Seattle. He is a registered Civil and Structural Engineer in State of Washington.

**LOUIS RUZZI** is the District Bridge Engineer for District 11-0 for Pennsylvania Department of Transportation (PennDOT). Ruzzi graduated from University of Pittsburgh at Johnstown, with a Bachelors of Science degree in Civil Engineering Technology, in 1980. He worked for a consulting firm for 4 years doing structural steel, concrete design and design of nuclear pipe supports/ instrumentation supports until 1985. Ruzzi has worked for PennDOT for over 25 years. He has spent 7 of those years in District 12-0 and 18 in District 11-0. At PennDOT he has worked in the Bridge Unit as a Bridge Designer, Bridge Inspection Squad Leader, and Assistant Bridge Engineer. For the past 11 years, Ruzzi has been the District Bridge Engineer for District 11-0. He is a member of American Association of State Highway and Transportation Officials (AASHTO) Highway Subcommittee on Bridges and Structures. Ruzzi is a licensed professional Engineer.

**MICHAEL SALAMON** is the Tunnel Superintendent for the Colorado Department of Transportation. He has been employed by the Colorado Department of Transportation since 1977. His entire career has been dedicated to the operation and management of the Eisenhower/Johnson Memorial Tunnels on Interstate 70. Salamon has been involved with every aspect of the operation of this 8900 ft, two tube tunnel with a current average daily traffic count of 30,000 vehicles. He is a member of American Association of State Highway and Transportation Officials (AASHTO) Highway Subcommittee on Bridges and Structures.

**FULVIO TONON** is an assistant professor at the University of Texas at Austin where he established the International Tunneling Consortium and a Master in Tunneling endorsed by the International Tunneling and Underground Space Association (ITA). Chair of the ASCE Rock Mechanics Committee and chair of the Research subcommittee for TRB Committee AFF60: Tunnels and Underground Structures, he has more than 14 years of research experience in the fields of geomechanics with emphasis on rock mechanics and rock engineering, numerical modeling in geomechanics, underground excavations and tunneling; uncertainty modeling, design process and optimization, and artificial intelligence as applied to Civil Engineering. He has published 2 books on tunneling, 40 papers in peer-reviewed journals and 35 papers in conference proceedings. Besides having more than 7 years of university teaching experience, he also has over 13 years of professional experience in geotechnical and structural engineering with projects completed in the Americas, Europe, and Africa. Design experience includes: cut-and-cover and bored tunnels in rock, soft ground and mixed face conditions, with or without the use of Tunnel Boring Machines; foundations and special foundations; rock and soil slope stabilizations; precast concrete and steel-concrete composite bridges; hydraulic infrastructures for dams, purification plants and rivers; renovations of ancient masonry buildings; and reinforced concrete buildings. He received his “Laurea” in Civil Engineering from the University of Padova, Italy, in 1994, a Ph.D. in Civil Engineering from the University of Colorado, Boulder, and he is a licensed Professional Engineer in Texas and Italy.

**MARY LOU RALLS** *(REPORT FACILITATOR)* is an engineering consultant and principal of Ralls Newman, LLC in Austin, TX, specializing in the advancement of structural engineering technologies. Before becoming an independent consultant in late 2004, Ralls was a structural engineer with the Texas Department of Transportation (TxDOT) for 20 years, the last five years as state bridge engineer and director of TxDOT's Bridge Division. In this position, Ralls was a member of the AASHTO Highway Subcommittee on Bridges and Structures and was chair of the Technical Committee for Security and vice chair of the Technical Committee for Research. Ralls earned her bachelor's and master's degrees in civil engineering from The University of Texas at Austin in 1981 and 1984, respectively, and became a licensed professional engineer in Texas in 1987. She was the report facilitator for the 2005 FHWA / AASHTO / NCHRP "Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response" international scan, the project manager for an expert panel to evaluate technical qualifications of proposing teams for the 2006 Florida Department of Transportation Port of Miami Tunnel and Access Improvement Project, and chair of a 2008 Maryland Transportation Authority Bridge & Tunnel Inspection Peer Review Panel. Ralls is chair of the Transportation Research Board's Design and Construction Group, which includes the Tunnels and Underground Structures Committee.