BEST PRACTICES FOR IMPLEMENTING QUALITY CONTROL AND QUALITY ASSURANCE FOR TUNNEL INSPECTION

Prepared for:

AASHTO Technical Committee for Tunnels (T-20)

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Disclaimers

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Disclaimer

Instructions to Panel Members

This project is being conducted for the *AASHTO Subcommittee on Bridges and Structures* as part of NCHRP Project 20-07/Task 261, *Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspection*. The report has not gone through the usual rigorous review process established and monitored by the Transportation Research Board Executive Committee or the Governing Board of the National Research Council, and should not be described as a “TRB Report”. It should be described as a contractor’s report conducted for the *AASHTO Technical Committee for Tunnels (T-20)* with funding provided through National Cooperative Highway Research Program Project 20-07/Task 261.

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NCHRP 20-07/Task 261

Best Practices for Implementing Quality Control and Quality Assurance for Tunnel Inspection

Introduction

Following the 2006 tragic ceiling collapse in the I-90 connector tunnel in Boston, Massachusetts, the National Transportation Safety Board (NTSB) recommended that a mandatory tunnel inspection program be developed to ensure the safety of our tunnels for the traveling public. The NTSB cited a need for improving practices used by state departments of transportation (DOTs) and transportation agencies for inspecting highway tunnels. While there are many different methods for inspecting tunnels, and varying degrees of inspection possible, there is no consistency across the country when it comes to tunnel inspection. In addition, there is limited experience and knowledge of tunnel inspection methods within state DOT's. To initiate a mandatory tunnel inspection program, guidelines are needed which would provide information and standards to enable states to select inspection methods that are most appropriate for their situations.

Inspection programs should be implemented for regular inventory and condition reporting that will be required as part of the upcoming National Tunnel Inspection Standards (NTIS) scheduled to be issued by the Federal Highway Administration (FHWA) in 2010. In addition to regular tunnel inspection frequencies for reporting requirements, tunnel owners should also implement inspections from a risk-based analysis approach that considers elements that typically deteriorate or malfunction within the tunnel and the severity of the impact from such problems. This could include inspections when there are major structural defects that could lead to imminent collapse, when structural defects could lead to a loss of serviceability (i.e. water leakage that could cause dangerous conditions for the traveling public), and when there are operational flaws that affect safe passage through the tunnel (i.e. flaws varying from fire safety issues to inadequate lighting to routine traffic flow). Other potential inspections for isolated items can be scheduled when there are periodic closings for minor repairs, replacement of lights, or routine maintenance.

Tunnel owners may also elect to categorize the various elements and systems to be inspected. Such inspections will involve different personnel based upon the type of inspection to be conducted. Also, appropriate inspection techniques and frequencies can be selected and implemented. Various categories could include:

Systems:	Structure Elements:
Communications	Arch
Drainage	Ceiling slab/architectural panels
Fire detection	Tunnel walls
Incident detection	Pavement slabs
Lighting	Pedestrian egress/safe rooms
Mechanical/electrical	Cross passageways
Traffic signals	Ancillary spaces
Ventilation	Portals

Processes

Emergency response (tow trucks, ambulance, police vehicles)
Fire prevention/response
Routine closures

Miscellaneous
Signs
Paint/striping
Tunnel surface condition (paint, tiles)

As noted above, there are systems and processes within a tunnel, besides the tunnel structure, that contribute to the overall operational safety within the tunnel. To provide the degree of safety for the traveling public, these systems/processes and the procedures that are followed in the event of an emergency must also be inspected and evaluated periodically. Very little documentation or guidance on this subject exists, and guidelines are needed to implement an overall tunnel inspection program across the country.

The research for this report documents current practices for tunnel inspection and for evaluating operational safety and emergency response systems. Recommended best practices are included, including a discussion of quality assurance (QA) measures for inspections, and achieving quality control (QC) of inspection findings. In addition, recommended data fields to be included as part of documenting the tunnel inventory and inspection results are provided.

Current Practices for Tunnel Inspection and Operational Safety/Emergency System Testing

Inspection Procedures
The Federal Highway Administration (FHWA) developed a *Highway and Rail Transit Tunnel Inspection Manual* in 2003 which was updated in 2005. This document provides guidelines for performing tunnel inspections, including guidance on inspection frequency, inspector qualifications, standardized condition definitions for various types of tunnel construction and equipment, procedures for rating elements within a tunnel, and recommended documentation. This document serves as a good starting point for development of tunnel inspection guidelines and will be discussed further later in this report.

The Task 1 Report for this project documented a literature search which detailed the state of the practice for tunnel inspection and included discussion of inspection frequencies, personnel performing inspections, and QC measures that are currently being used in the U.S. The literature search was extended also to international tunnel owners to review their latest techniques for performing inspections and current plans to improve inspection results. A survey of highway and rail transit tunnel owners in the U.S. was also performed in November 2008 to obtain additional information on the state of the practice for tunnel inspection. 32 highway and 11 transit owners responded to the questionnaire. A brief synopsis of the findings from the Task 1 Report is provided below, from which best practices will be developed later in this report.

Inspection Methods and Frequency
It has been established that both highway and rail transit tunnel owners are inspecting their tunnels on a regular basis. Most of these inspections to date in the U.S. have been visual inspections that have been supplemented with both destructive testing (concrete or wood cores) and non-destructive testing (dMeters, pacometers, infrared thermography, ground penetrating radar, oil and vibration testing), where deemed appropriate. For highway tunnels, inspections

range from daily reviews of mechanical/electrical systems, monthly visual inspections of structural elements, and more thorough inspections every two years, with some owners extending the frequency of thorough inspections up to five to ten years. For transit tunnel owners, the inspection of track and signal/train control systems usually occurs daily. The agencies then conduct other inspections weekly, monthly, bi-monthly, semi-annually, and yearly. Inspection frequency for both highway and transit tunnels is typically dictated by the condition of the tunnel elements being monitored.

The international literature search revealed that considerably more effort is being undertaken to advance other inspection methods for efficiency gain in typical in-depth inspections, while providing more valuable information than visual inspections. Although various technologies have been employed, the most common non-destructive techniques being recommended for further development include ground penetrating radar, infrared thermography, and laser scanning. But, researchers in Europe admit that hands-on, visual inspections are necessary to supplement the non-destructive inspection methods, and often destructive methods are also necessary to validate non-destructive testing results.

Inspector Qualifications

For both highway and transit tunnel owners, most inspections are conducted by tunnel in-house staff. Often the inspectors are maintenance staff working for the agency or staffed at the tunnel. Consultant staff is used by several owners, and in these cases the inspection is typically led by a professional engineer.

Inspection Procedures

A majority of highway and rail transit tunnel owners utilize documented procedures for the inspections. Most of these procedures are in the form of manuals and guides. Several states use their bridge inspection coding manual to assign condition ratings and include some inventory items, like roadway width, vertical clearance measurements, etc. A few agencies are currently using FHWA's *2005 Highway and Rail Transit Tunnel Inspection Manual* for tunnel inspection procedures.

Inspection Documentation

Highway and rail transit tunnel owners maintain documentation of inspection results. Some tunnel owners utilize computerized databases for tunnel condition data, while most maintain spread sheets, field notes/sketches, and written reports for inspection documentation.

QA/QC Measures

Approximately 50 percent of highway tunnel owners and 75 percent of transit tunnel owners require QA/QC policies and procedures to be submitted. However this is typically general documentation of company quality policies; it is not clear from the survey results whether specific documentation is required by agencies for achieving quality inspection results. However, approximately 50 percent of highway tunnel owners and 75 percent of transit tunnel owners indicated they perform QC of inspection findings performed by their in-house personnel by spot checking the results in the field. When professional engineers or qualified persons are engaged to perform the inspections, the agencies generally accept the professional's/qualified person's opinion without any further verification. When asked if field quality control reviews are for high-risk elements, about 33 percent of tunnel owners perform such reviews.

Operational Safety and Emergency Response System Testing
The results of the November 2008 questionnaire and the literature search on emergency response systems in tunnels are documented below. Most of the literature search from Europe reveals significant effort in rating the tunnels for safety based upon the components designed and installed within the tunnel envelope.

Survey Results
Since the National Cooperative Highway Research Program's (NCHRP's) Project 20-07/Task 261 research also included operational and emergency systems response testing, the questionnaire developed in November 2008 as part of this project gathered data on such information from current highway and rail transit tunnel owners in the U.S. The questions and responses are indicated below for the 32 highway and 11 transit owners responding to the questionnaire; specific comments made by the owners are also shown below the results. A brief summary will follow the responses.

a. What Emergency Systems do you have in place for your tunnel?
Number of respondents = 31 for highway and 11 for transit.

	Highway	Transit
1) Emergency Communications	21	9
Hardwired Telephones	19	8
Radio and Cell Phone Repeaters	20	9
Other, please specify		

Highway
- 911 WIN paging system; Motorists Aid Call Box; video; too short for communications inside tunnel; none (four); Supervisory Control and Data Acquisition (SCADA) System; AM-FM Rebroadcast system; Variable Message System (VMS) overhead signs in the Canyon ahead of the tunnels – northbound and southbound; Delaware DOT has installed cell antenna to enhance wireless communication; Wyoming DOT's (WYDOT's) Tunnels A and B – telephone to control lighting/ventilation; Pennsylvania uses a 800 MHZ radio system for communications.

Transit
- Emergency Command Posts at underground stations; cell phone antennas within tunnels; Maryland Transit Administration police radios work in tunnel; repeaters will be available near end of fiscal year (FY) 2009

	Highway	Transit
2) Fire and Incident Detection	23	8
Automatic Fire Detection on Roadway	7	2
Linear Heat Wire	7	0
Flame Detector	1	2

	Highway	Transit
Spot Detectors	3	3
Manual Fire Pull Stations	16	8
Closed Circuit Television (CCTV) Camera	23	8
At Portals	18	6
Within Tunnel	21	4
Other, please specify		

Highway

- None (four); cameras part of light fixtures in Vista Ridge tunnels; carbon monoxide (CO) detection system; cameras in Tunnel A only; installed devises vary per location; various means of fire and incident detection – specific information not being provided; long corridor with views into tunnels

Transit

- None; CCTV cameras in Station areas only; Dallas Area Rapid Transit (DART) police patrol; CCTV Cameras are also installed at all underground stations

	Highway	Transit
3) Emergency Lighting	21	5
Integral Battery Pack Lighting Fixtures	8	4
Centralized Uninterruptable Power Supply (UPS)	15	5
Generator	19	5
Diesel	15	2
Natural Gas	3	2
Propane	1	0
Dual Utility Service	16	3
Other, please specify		

Highway

- None (three); UPS for tunnel lighting; wired in from two sub-stations in Elk Creek; diesel back up for Knowles Creek up until 1996; lighting on several circuits in Vista Ridge tunnels; battery bank

Transit

- None; generator at San Francisco Municipal Railway (MUNI) Metro turnback only

	Highway	Transit
4) Fire Suppression	26	10
Portable Fire Extinguishers	26	7
Fire Department Hose Connection	20	10
Hydrants	13	3
Water Supply	18	5
Private Water Supply w/ Storage Tank	7	0
Public	14	6
Fire Pump	9	1
Electric	9	2

Diesel	2	0
Dual-Electric Utility Service	9	0
Fixed Fire System	4	5
Sprinklers	5	4
Deluge	2	4
Other, please specify		

<u>Highway</u>
- Sprinklers located in each sump; two T-100 Fire trucks with water, foam and dry chemical agents, operated by a full staffed industrial fire brigade trained in site specific incidents; ANSEL system (control room); none (three); above ground hydrant with standpipe connection in tunnel; water pressure redundancy via either of the two vent buildings; fire extinguishers in the Vista Ridge tunnels; ceramic tile liners; portable fire extinguishers at Tunnel A only; deluge system in Lehigh Tunnel #1 protecting reversible fans; fire standpipe system; dry suppressant

<u>Transit</u>
- Dry standpipe systems in the underground stations; none

	Highway	Transit
5) <u>Drainage Discharge Path</u>	21	8
On Site Water Retention Basin	8	1
Storm Water	18	8
Combined Storm/Sewer System	8	3
Pumping Station	14	8
Hydrocarbon Detection	6	0
Other, please specify		

<u>Highway</u>
- Sumps; CO indicators; none; natural drainage flow at all tunnels; weep holes in concrete liners flow into inlets, pipes, catch-basins; drainage fabric behind some liners; drain pipes at edge of pavement to retention boxes for filtering and then discharge to regular drainage system; various systems in place.

<u>Transit</u>
None

	Highway	Transit
6) <u>Tunnel Ventilation</u>	21	6
Mechanical (Normal Operation)	18	6
Manual Operation	14	5
Automatic Operation	16	6
Natural	15	2
Emergency	18	7
Manual Operation	16	6
Automatic Operation	13	5
Other, please specify		

Highway
- Jet Fans – automatic and/or manual; Tunnels A and C – natural ventilation (WYDOT); Tunnel B – automatic ventilation system is set up on a timer to activate fans at certain times (WYDOT); none

Transit
- None; mechanical in select stations, otherwise natural in tunnels

	Highway	Transit
7) Traffic Control	21	2
Lane Signals	20	1
Portal Mounted	17	1
Within Tunnel	11	2
Automatic Barriers	3	0
Traffic Status Monitoring	12	2
Loop Detectors	8	2
Microwave/Radar Speed Detection	3	0
Other, please specify		

Highway
- Photo enforcement cameras within 1/4 mile of entrance and exit; VMS (two); California Highway Patrol /tunnel crews (two); none (four); traffic observed by CCTV and manned patrols; traffic congestion; bike/pedestrian signs at the ends of some tunnels; tunnel middle wall; stop lights to stop traffic if tunnel is blocked for any reason; CCTV cameras

Transit
- Central Control monitors the vehicles in the tunnel via SCADA; rail tunnels utilizing track signals; Automatic Train Control System (ATCS).

	Highway	Transit
8) Over Height Vehicle Detection System		
Yes	15	0
No	18	9
If yes, describe your over height vehicle detection system		
Fixed Bar or Apparatus above roadway	5	0
Light or Other Sensors that sound an alarm	11	0
Variable Message Sign	8	0
Other, please specify		

Highway
Vehicles checked at toll booth by humans prior to entry; advanced warning signs; alarm bells

Transit
None

		Highway	Transit
9)	Pedestrian Egress	18	8
	Exit Path Signage	11	8
	Cross Passageways within 650 feet of each other	12	3
	Emergency Exits within 1,000 feet of any point in tunnel	5	5
	Pedestrian Sidewalks	16	4
	Safe Rooms	4	0
	Other, please specify		

Highway

Cross passageways; emergency exits at vent buildings; 2’-8” walks 3’-6” above roadway; wide curbs only in tunnels with narrow shoulders; cross passage in the middle of the 232 foot long tunnels; narrow walkways at Tunnels A and B (WYDOT); egress plans in place – specific details are not being provided.

Transit

No comments

The nine questions listed above regarding “emergency systems” were asked in the survey to provide an idea of what emergency systems exist in tunnels across the U.S. A brief synopsis of the results is as follows:

1) Emergency Communications – 62 percent of the highway tunnel owners and 82 percent of the transit tunnel owners responded that they have some type of emergency communications available at the tunnel, with radio and cell phone repeaters being the most predominant type and hard-wired telephones just slightly behind.

2) Fire and Incident Detection – The two predominant types of detection equipment include CCTV cameras and manual fire pull stations (72 percent of both highway and rail transit tunnel owners). Other equipment that is used is relatively small in comparison to the existence of these two detection systems.

3) Emergency Lighting – 66 percent of highway tunnel owners and 45 percent of transit tunnel owners have emergency lighting in their tunnels. For those owners who responded, a diesel emergency generator is generally used for backup, although a centralized UPS is also available at many of the tunnels. In addition, 50 percent of highway tunnels identified that dual utility service is available.

4) Fire Suppression – Portable fire extinguishers are used by 81 percent of the responding highway tunnel owners and by 64 percent of the transit tunnels. In addition, 62 percent of the responding highway tunnel owners and 91 percent of responding transit tunnel owners indicated hose connections exist for fire department access. To a lesser degree, fire hydrants, water supply systems, and fire pumps exist at certain tunnels.

5) Drainage Discharge Path – 56 percent of highway tunnel owners and 73 percent of transit tunnel owners have storm water systems present at the tunnels; pumping stations are

6) Tunnel Ventilation – 56 percent of highway tunnel owners and 54 percent of transit tunnel owners have mechanical ventilation in their tunnels. Automatic operation of the ventilation systems is slightly greater than manual operation for both normal and emergency conditions. 47 percent of the highway tunnel owners and 18 percent of transit tunnel owners have natural ventilation at their tunnels.

7) Traffic Control – Lane signals are the predominant method for traffic control in highway tunnels with 62 percent of the owners reporting them to be at the portals and 53 percent within the tunnel. To a lesser degree, highway tunnel owners have loop detectors and microwave/radar speed detection devices in the tunnels. As anticipated, relatively few transit tunnel owners (18 percent) require traffic control.

8) Over-Height Vehicle Detection Systems – 47 percent of highway tunnel owners have over-height detection systems utilizing a light or other sensor system that sounds an alarm when an over-height vehicle is approaching. Other systems used include variable message signs and fixed apparatus above the roadway.

9) Pedestrian Egress – This is extremely important in the event of a catastrophic event at the tunnel. 56 percent of highway tunnel owners and 73 percent of transit tunnel owners have some form of pedestrian egress. Pedestrian sidewalks are the most predominant means of pedestrian egress in highway tunnels (50 percent of owners responding) whereas exit path signage is used predominantly to direct pedestrians in the event of emergency in transit tunnels (73 percent of transit owners). 38 percent of highway tunnel owners have cross passageways within 650 feet of each other as required by National Fire Protection Association (NFPA) 502. 12 percent of highway tunnel owners stated that safe rooms exist in their tunnels for emergencies. Safe rooms are not present in transit tunnels per those that responded.

Do you have Emergency Response Plans in Place for your Tunnels?
Number of respondents = 31 for highway and 11 for transit.

	Highway	Transit
1) Do you have an Emergency Response Plan in place for Incident Management or Catastrophic Event (fire, natural disaster, etc.)?		
Yes	24	10
No	9	1

	Highway	Transit
2) If yes, are the logical steps for the emergency response clearly defined for the tunnel operator?		
Yes	20	10
No	7	0

	Highway	Transit
3) Do you, at regular intervals, perform tests of the emergency response plan (i.e. practice drills, etc.)?		
Yes	15	7
No	14	4

	Highway	Transit
4) If yes, indicate frequency in months		
6 months	4	1
12 months	7	6
24 months	2	0
Other, please specify		

Highway

- Informational meetings with fire department; quarterly; every two-three years; 6-12 months for various tests

Transit

They have been done but not in last two years; and Agency Emergency System has recently been developed. Certain components of the system are monitored through maintenance programs at this point.

	Highway	Transit
5) If so, who participates?		
Police	10	8
Fire	11	8
Emergency Medical	9	8
HAZMAT	9	4
Utilities	2	1
Media	2	5
Other, please specify		

Highway

- Tunnel crews; Caltrans tunnel crew via safety meeting; tunnel staff; Operations uniformed force and Queens Midtown Tunnel maintenance; emergency management personnel; Oregon Department of Transportation maintenance, HAZMAT, and region headquarters personnel; facility staff

Transit

- MUNI employees; Maryland Transit Administration Operations personnel

As noted from these five questions, emergency response plans have been developed for incident management in the tunnel for 77 percent of highway tunnel owners and 91 percent of transit tunnel owners, indicating that tunnel owners have taken steps operationally to protect the traveling public during emergency events. A majority of both highway and transit owners having emergency response plans (83 percent for highway and 100 percent for transit) felt that their plans were clearly defined so the tunnel operator could proceed with the necessary steps depending upon the emergency that occurs.

When asked if tests (practice drills) are performed at regular intervals on the prescribed plans, only 62 percent of highway tunnel owners and 70 percent of transit tunnel owners perform such tests on a regular basis, with the majority responding they are performed every 12 months. During these tests, a variety of other agencies are generally invited to participate. These include police, fire, emergency medical, and hazardous materials agencies.

<u>Results of Literature Search</u>

World Road Association Recommendations – For more than 30 years European countries have shown growing interest in the use of classification systems for establishing consistent, safe and economic standards for equipping, operating, maintaining and refurbishing highway tunnels. The Tunnel Committee for the Permanent International Association of Road Congresses (PIARC), which is now known as the World Road Association, authorized a paper by F. H. Amundsen and O. L. Sovik of Norway titled "*Classification of Tunnels, Existing Guidelines and Experiences, Recommendations*" at the XXth World Road Conference in Montreal in 1995. This paper was a follow up to PIARC's Operation, Maintenance, and Management working group reviewing "*Safety – Safety Equipment – Fire Fighting Facilities and Equipment*" presented at the XVIIIth World Congress in Brussels in 1987. The Tunnel Committee reported that the results of the 1987 paper were still valid but that increased technology led them to make new 1995 recommendations for classification of tunnels (length, traffic, one or two way, urban or rural, oversea or subsea), safety equipment for emergency and evacuation aid (road signs, lights, telephones, radio communications, loudspeakers, fire extinguishers, fire hydrants, etc.), traffic regulators (lane signals, blinking red lights, VMS, barriers, and over height vehicle control), and for tunnel operation systems (data control of equipment from control room - programmable logic systems, CCTV, and emergency plans). The committee also recommended that all tunnels exceeding 500 meters in length should have such an emergency plan that was coordinated with local fire and police personnel.

SIRTAKI Project – Antonio Marques and Manual Serrano of GRUPO ETRA, Spain in their paper "*Decision Support for Emergency in Roads*" delivered at the Second International Symposium in Lausanne, Switzerland in 2006 introduced the SIRTAKI Project, which was promoted by the European Union. This project consisted of development of an advanced Decision Support System (DSS) that is focused on tunnel management and emergencies. The system is comprised of four modules as follows:

- Knowledge Basis Module – This module contains specific data on the tunnel and provides mitigation measures and actions to manage a developing incident in the best manner possible.
- Inference Module – This module assists tunnel operators to make decisions in emergency situations by identifying potentially dangerous situations through a pattern matching process.
- Tunnel Model – This module provides real time information regarding the status of the tunnel and other SIRTAKI modules.

- Tunnel Operator Working Environment – This is the graphical user interface and geographic information system (GIS) that reflects the operation of all modules of the system.

This system was piloted in Spain and Italy on both highway and rail passenger tunnels. The tests indicated that the use of the SIRTAKI system reduced the detection time of incidents and improved the decision making process and coordination of responding tunnel personnel.

European Tunnel Assistance Program (EuroTAP) – Europe began benchmarking tunnel safety annually, beginning in 1999, through a consortium of 12 Euro Test automotive clubs from various European countries. In January of 2005, EuroTAP was launched as a result of the 1995 to 2005 annual test results. As of 2005, 14 countries from the United Kingdom to Italy were taking part in the annual safety inspections. As stated in news from Euro Test's website on April 4, 2005, the inspections have a two-fold objective: to determine each tunnel's safety potential – the presence of elements that serve to prevent or contain emergency situations; and to calculate each tunnel's risk potential – the likelihood of incidents occurring that could lead to accidents and the possible extent of damage that could be caused as a result. According to EuroTAP's newsletter on the "*Future of Tunnel Testing – EuroTAP 2007*", each tunnel is subjected to a checklist which includes such items as:

1) Tunnel system – number of tubes, brightness of walls, width of lanes, and geometry.
2) Lighting and power supply – lighting and transition zones, power and emergency power supply.
3) Traffic and traffic surveillance – congestion, restrictions of hazardous materials, closure measures, signs, traffic management and control, visual equipment, video surveillance, automatic traffic recording, control center, etc.
4) Communications – radio (both traffic and tunnel), loudspeakers, and emergency phones.
5) Escape and rescue routes - evacuation lighting and escape route signs, fire resistant doors to escape areas, distance between emergency exits, and access for rescue services.
6) Fire protection – tunnel structure, cables, drainage system for flammable and toxic liquids, fire alarms, and extinguishing systems.
7) Ventilation – normal mode, control of longitudinal flow, temperature stability, system testing, and longitudinal ventilation.
8) Emergency management – training, maintenance plans, emergency response plans, automatic linking of emergency systems, and emergency drills.

The results in 2007 on 51 tunnels reviewed in 13 countries revealed the following ratings: Very good – 18 tunnels, Good – 11 tunnels, Acceptable – 12 tunnels, Poor – 3 tunnels, and Very Poor – 7 tunnels.

International Technology Scan - The FHWA, in cooperation with American Association of State Highway and Transportation Officials (AASHTO) and NCHRP, conducted an international technology scan of nine European countries in September and October of 2005 with an 11-member team to learn about current practices for underground transportation systems in areas of safety, operations, and emergency response. The focus of the scan was on equipment, systems and procedures incorporated into the European tunnels and the results were documented in their report "*Underground Transportation; Systems in Europe: Safety, Operations, and Emergency*

Response", AASHTO in cooperation with NCHRP, June 2006. The team members suggested that nine initiatives/practices be considered for future highway tunnel designs/rehabilitations in the U.S.:

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

Although all nine initiatives are important to consider in tunnel design, rehabilitation and inspection, recommendations 1, 5, 7, 8, and 9 are most applicable to tunnel inspection procedures and operational safety and emergency system testing.

The 2005 technology scan was followed in 2007 by similar research performed as NCHRP Project 20-07/Task 230. The results of this project were produced in a Final Report on "*Safety & Security in Roadway Tunnels"*, K. Almand, Fire Protection Research Foundation, Quincy, MA, March 2008. The project's panel identified 12 areas of research related to safety and security that should be addressed in future research.

<u>Recommended Best Practices for Tunnel Inspection</u>

The FHWA Tunnel Inspection Manual was intended to be a living document that could be supplemented over time to meet future inspection needs that address advances in technology and materials. In fact, the original 2003 Manual was updated in 2005, which is the current one available on the FHWA website for download by highway and rail transit tunnel owners. It is also understood that the Federal Railroad Administration (FRA) has recently implemented its own requirements for tunnel inspection, documentation and reporting of freight railroads.

Several DOT personnel in various states, along with national organizations, private engineering consultants and selective code officials responded to FHWA's Advanced Proposed Rule Making for National Tunnel Inspection Standards (NTIS) in June, 2009. Although NTIS requirements are not yet developed nor required by FHWA, the questions presented and the responses of industry back to the FHWA are directly applicable to this Task 261 Project for best practices for tunnel inspection. It was clear from the responses received from this group of engineering consultants, code personnel and tunnel owners that the Tunnel Inspection Manual was an excellent start in aiding tunnel owners to establish a consistent process for conducting, evaluating and documenting their tunnel inspections, but that additional information should be included to either supplement or modify current information presented in the Manual. The best practices documented below includes some of the suggested modifications/additions to the current FHWA Highway and Rail Transit Tunnel Inspection Manual as well as other recommended best practices resulting from the literature reviewed.

QA/QC of Tunnel Inspections

Quality in the inspection and the resulting documentation is an important aspect that must be considered to ensure the safety of the traveling public in tunnels. The definitions for QC and QA used in this report are as follows:

QC refers to quality related activities associated with the creation of project deliverables, i.e. the inspection results. QC is used to verify that deliverables are of acceptable quality and that they are complete and correct. Examples of QC activities include peer reviews of deliverable products from the inspection documentation and verifying the findings in the field are as recorded by the inspector.

QA refers to the process used to create a quality product or deliverable, (or in this case inspection) and can be performed by a manager, client, or even a third-party reviewer. Examples of QA for tunnel inspections include the establishment of guidelines or checklists that would lead to quality inspections, creating minimum inspector qualifications, establishing condition rating requirements that yield consistency between inspection periods, requiring that equipment be calibrated, having testing personnel submit certifications on the equipment being used, developing standard inspection forms with data fields included, and following standard processes/procedures for performing inspections.

Both QC and QA must be performed to ensure that the inspections conducted and deliverables produced meet the tunnel owner's quality requirements, while ultimately ensuring the public's safety.

Tunnel Inspection Best Practices

To achieve quality inspections, it is suggested that the following best practices be implemented for a successful inspection program. These practices were previously introduced in the FHWA's 2005 *Highway and Rail Transit Tunnel Inspection Manual*.

Mobilization

Once the tunnel owner has decided upon the degree of the inspection, a plan should be put in place to accomplish the inspection with the least disruption to operations and the traveling public. For daily, weekly, or monthly walk-through inspections by tunnel staff to check on the operation of mechanical/electrical equipment that are in portal buildings or ventilation buildings outside the roadway, there is no need for any significant mobilization planning. But, if the tunnel owner is requesting that a priority or planned routine inspection be conducted that includes the main tunnel area, then the staff involved with the inspection needs to develop appropriate plans to achieve consistency of results and as much efficiency as possible during the inspection. Also, if scheduled shutdowns of the tunnel roadway or rail track bed occur for other reasons, this is another opportunity to inspect selected elements during the shutdown.

Depending upon the location of the equipment or structure to be inspected and whether such locations are within the tunnel roadway or rail track bed, then the lead member of the staff conducting the inspections, whether it is tunnel staff, consultant staff, or testing agency personnel, should prepare appropriately for the inspection. Preparations would include coordination necessary to establish maintenance and protection of traffic, shutting down the third rail if a transit tunnel, coordinating hours available for access within the tunnel and ancillary spaces, obtaining the equipment needed to perform the inspection, review of tunnel construction drawings and previous repairs/modifications, review of previous inspection reports, development of field forms to expedite the inspection (whether on paper or on pen tablet hand-held computers), setting a survey control (if this is the first time an in-depth inspection has occurred in the tunnel) such as the one established in the 2005 Tunnel Inspection Manual, and coordinating the teams and training the selected inspection staff of the work to be accomplished. By accomplishing such pre-inspection plans as required during this phase, the length of closure periods for conducting the tunnel inspection within the tunnel roadway or track bed will be minimized. In addition, the QA measures undertaken during this period will provide the tools/procedures that will contribute to good quality for the overall inspection.

Inspector Qualifications and Training
A large inspection may be performed by multiple teams of different disciplines, with each team made up of a Team Leader and Team Members, and each discipline led by a Discipline Lead Inspector. The Tunnel Inspection Manual suggested that inspection teams be comprised of a minimum of two people, both of whom should meet minimum guidelines. It is recommended that the lead inspector for each team (the Team Leader) be a registered professional engineer having experience in tunnel design or tunnel inspection and having knowledge of the specific types of materials and systems comprising the tunnel being inspected. If the Team Leader is not a professional engineer, it is recommended that a minimum number of years of inspection experience related to the elements/systems being inspected be required. Recommended minimum years of experience are: civil/structural elements – five years, mechanical systems – three years, electrical systems – three years, and track/third rail/catenary/signals/communications – three years. If the Team Leader is a Professional Engineer with adequate experience, other team members are acceptable provided they have at least one year of inspection experience with the discipline’s elements/systems. In addition, some states currently are using the National Bridge Inspection Standards (NBIS) qualifications for their personnel performing tunnel inspections. These NBIS qualifications will likely be updated by FHWA specifically for tunnels when new NTIS standards are scheduled for issue in 2010.

In addition, the Discipline Leader should be familiar with applicable codes for the types of elements/systems being inspected. For the mechanical, electrical, and lighting systems inspection, the Discipline Leader, which is often also the only Team Leader, should be a professional engineer or have a minimum of three years of experience in tunnel inspection, design, or construction for that system. This would allow for experienced contractors and designers, as well as engineers, to be the lead inspector. In addition to the Team Leader, other inspection personnel may be supplemented based on scheduling needs, special needs or conditions, and qualifications to supplement and support the inspection process. Minimum requirements for other inspectors include basic knowledge of the systems located within the tunnel and one year inspection experience with the types of systems they are tasked with evaluating.

Inspection teams should consist of a two-person crew, as a minimum, for safety reasons and in order to maximize efficiency with the many duties that the inspectors must perform. Multiple two-person crews or combinations of three-person crews may be used, depending upon the scope and schedule. The number of crew members and number of crews should be determined by the Discipline Lead Inspector. Mechanical and electrical inspection teams are often one- or two-person teams due to the extent of the inspection required. In many cases the mechanical and electrical inspectors can work together to reduce the number of inspectors while provide the necessary inspection support, especially given the integration of the systems they are inspecting. The size and number of crews should also be set based upon conversations with the tunnel owner during the mobilization/planning stage so that minimal disruptions occur with on-going operations.

The best practice of having a professional structural engineer to be in overall charge of a structural inspection is endorsed by all those responding to the Advanced Proposed Rule Making for NTIS by FHWA and this practice should be followed by all tunnel owners. If the tunnel is an exposed rock tunnel, then the lead individual for the overall inspection should be a professional geologist with knowledge of the rock strata and its general characteristics. If the tunnel is comprised of a concrete-lined rock bore, where the shell is a structural element supporting the rock forces, then a structural engineer should lead the inspection to interpret liner distress resulting from a build-up of rock forces. The assistant on the team should be a geologist since this person will need to evaluate the rock stability. The geologist will assist the structural engineer in identifying locations that should be inspected more closely or which will need some form of non destructive testing to determine the structural viability of the liner.

The 2005 *Highway and Rail Transit Tunnel Inspection Manual* did not address training of individuals, but did require that the inspector have certain qualifications. It is recommended that training should be a requirement for tunnel inspectors, similar to that received for bridge inspectors on a national level, to provide knowledge of tunnel structural behavior and system requirements, life safety code requirements, and to achieve consistency in the inspections from a national perspective. Also, as current materials, new materials, and new equipment are used in the future, training on such materials/equipment is appropriate for proper evaluation. It is suggested that FHWA and the Federal Transit Administration (FTA) take the lead to develop appropriate training courses for each discipline, unless the federal agencies permit states the flexibility to develop and implement their own training courses. Items to be included in this training should include, but not be limited to, general knowledge of tunnel structural behavior; general characteristics of concrete, steel, cast iron, brick, and wood; typical deficiencies for each of these materials; definitions for minor, moderate, and severe deficiencies; how to select condition evaluation ratings for various elements by use of descriptions and photos; and the approach for conducting inspections and documenting deficiencies. For mechanical and electrical inspectors training should include, but not be limited to, review of the different types of fans used in tunnels and how they operate, items to be inspected and various tests for mechanical and electrical systems, and applicable codes and standards for tunnels. Safety requirements and personal equipment should be reviewed with all inspectors.

These training courses should be held at regular intervals from which inspectors can develop appropriate credentials to assist in tunnel inspections. The specific requirements and schedule for additional or refresher training should be established by FHWA and FTA as part of their overall program. Each inspector should receive a certificate of completion of each course attended and have it available to any tunnel owner to prove qualifications for the task being assigned. This is one method to satisfy that quality assurance practices are being engaged by the owner prior to having inspection commence within their tunnel facilities.

Testing

Mechanical and electrical equipment testing often involves the use of outside testing firms to perform operational testing and condition analysis of the equipment. The use of nationally accredited testing firms should be used to the extent possible to make sure of the quality and accuracy of the testing. Some of the possible tests to perform on tunnel systems are listed below. This is not meant to be a complete list, but rather a sampling of tests that might be performed:

- Vibration analysis for rotating or reciprocating equipment
- Infrared monitoring of electrical equipment and connections
- Pump capacity testing – fire pumps, well pumps, etc.
- Air flow testing
- Generator testing under load
- Primary power line insulation testing
- Transformer tests (i.e. oil condition, turns ratio)
- Oil analysis of fan bearing oil
- Operational tests of heat detection, fire alarm and deluge systems
- Operational tests of CO monitoring system.

Inspection Frequency

The FHWA's Tunnel Inspection Manual states for civil/structural elements that "*The tunnel operator should establish the frequency for up-close inspections of the tunnel structure based on the age and condition of the tunnel. For new tunnels, this time period could be as great as five years. For older tunnels, a much more frequent inspection time period may be required, possibly every two years. This up-close inspection is in addition to daily, weekly, or monthly walk-through general inspections.*"

Similarly, the Tunnel Inspection Manual states for both mechanical and electrical systems inspections "*that if a proper preventive maintenance program is strictly adhered to, the main purpose of an in-depth inspection of these systems is to verify that the mechanical/electrical systems are performing as expected.*" The Manual further states "*It is up to the tunnel owner to determine the frequency of the in-depth inspections for the mechanical/electrical systems. They can be performed concurrently with the civil/structural inspections or as deemed necessary by the owner because of the age of the equipment and the amount of equipment needed for proper tunnel operation.*"

Though not specifically stated, these frequencies were intended to be risk-based; frequencies were to be established from the condition, age, maintenance, previous history, traffic conditions, etc., of the elements to be inspected. The Manual left the selected inspection frequency up to the tunnel owner, who best knows the condition of their tunnel(s). These concepts echo comments received from various parties responding to FHWA's Advanced Proposed Rule Making for NTIS, who indicated that inspection frequency should be established based on the conditions that exist.

Until Congress establishes national requirements for inspection reporting, each tunnel owner is free to inspect his tunnels when he chooses without any submission necessary to FHWA and FTA, other than what is submitted via the Bridge Structure Inventory and Appraisal (SI&A) forms. Currently, bridges must be inspected and results submitted to FHWA on a two-year recurring cycle. This should be the minimum that FHWA/FTA would require for tunnels, but it is recommended that newer tunnels be permitted to extend inspection frequency for up to five years, depending on age and condition.

For the mechanical and electrical systems, inspection frequencies should follow the schedule for structural inspection as a minimum. The frequency for inspection of these systems should be established based on the mean time between failures for the particular system. The time may vary based on risk assessment and the degree of routine maintenance performed. Systems related to safety might require a visual inspection at closer intervals, possibly daily or even monthly. The mechanical and electrical equipment for tunnels will require an increased level of inspection as the tunnel ages. While mechanical and electrical equipment are not likely to be the direct cause of an incident (as a structural failure might be), these systems are required to mitigate potential issues within the tunnel. Failure of these systems during an incident – when they are required to operate far above the base line operating level – could result in a significant increase in damage to the facility, potential hazards to the public, and, in the worse case, death.

Condition Ratings

Standardized condition ratings allow inspections to be performed by multiple teams over the life of the tunnel, with consistent results. If all inspectors are using the same definitions and ratings, the results can be readily compared from one inspection period to the next.

The *Tunnel Inspection Manual* provided a numerical rating system of 0 to 9 for the various structural elements, with 0 being the worst condition and 9 being the best condition. General descriptions for these are as follows:

- 0 - Critical Condition: Structure is closed and beyond repair.
- 1 - Critical Condition: Immediate closure required. Study should be performed to determine the feasibility of repairing the structure.
- 2 - Serious Condition: Major repairs required immediately to keep structure open to highway and rail transit traffic.
- 3 - Poor Condition: Major repairs are required and element is not functioning as originally designed. Severe defects are present.
- 4 - Shading between "3" and "5".
- 5 - Fair Condition: Minor repairs required but element is functioning as originally designed. Minor, moderate, and isolated severe defects are present but with no significant section loss.
- 6 - Shading between "5" and "7".
- 7 - Good Condition: No repairs necessary. Isolated defects found.

- 8 - Excellent Condition: No defects found.
- 9 - Newly Completed Construction.

This rating system was a modified form of the one described in the *Bridge Inspector's Training Manual* published by FHWA. However, it was modified in the Tunnel Inspection Manual for various tunnel liners, including cut-and-cover box tunnels, concrete/shotcrete inner liners, soft-ground tunnel liners, rock tunnels, and timber liners.

Although no specific condition ratings were provided for mechanical or electrical components, the Tunnel Inspection Manual included the following statement: "*If a tunnel owner desires to use this condition code system for mechanical or electrical systems or other tunnel appurtenances, then the codes can be adapted to represent a smaller set of conditions. An example would be to give numbers to the following conditions: excellent, good, fair, poor and serious. This may be done to track conditions through the use of a tunnel management system.*"

It is possible to assign condition ratings to the mechanical/electrical systems. The condition ratings for these systems are not appropriate for the 10-point scale used for structural ratings. It would be more appropriate to limit the number of condition ratings to 5 for such systems, as is indicated by the following:

- 0 – Non-operational: Out of commission.
- 1 – Restricted Use Equipment: One or more components not operating over full design range (ex. Fan can run on low speed only, etc.).
- 2 – Fair Condition: Equipment exhibits no restricted operation or safety issues; maintained but minor leakage or damage present.
- 3 – Good Condition: Clean, no evidence of leakage or damage, well maintained.
- 4 – New or Like New Equipment: First one-three years of equipment life.

Structural Inspection Methods

Until non-destructive methods similar to those mentioned above being studied in Europe (ground penetrating radar, thermography/visual, laser scanning) have been more widely refined to gather the information desired, tunnel owners in the U.S. will undoubtedly continue with non-destructive methods (hammer tappings and visual observations) as the primary means of inspecting the exposed surfaces of the concrete-lined tunnels to determine the condition of the tunnel linings. This inspection method provides information on concrete surface soundness, delaminations, cracks, spalls, leakage, etc. Additional non-destructive methods that should be considered include a deflection profile of the tunnel to see how it deviates from a set baseline. If a tunnel is found to be settling in one location, this will alert the inspectors to monitor for settlement induced distress. Also, a side scan sonar or multi-beam sonar should be considered to see if the cover over the tunnel is intact or if it has been dislodged and the tunnel shell is exposed. For wood and cast iron/steel liner plate tunnels, no non-destructive testing is currently being developed as far as the literature search revealed, although using dMeter readings for thickness of steel liner plates is currently readily available. As is currently the practice with many tunnel owners, these methods of visual inspections, supplemented with relatively small tools (hammers for concrete, pacometers to locate reinforcing steel, impact-echo for non-destructive testing of concrete through-thickness, awls for wood, and measurement gauges for steel plate thickness readings), and destructive testing methods (concrete cores where deemed necessary for liner thickness verification, freeze-thaw resistance for concrete condition, petrographic testing of the concrete structure, and wood cores for further definition of wood condition) are recommended to provide tunnel owners a realistic assessment of the structural condition of the main tunnel structure.

Where certain defects such as suspected voids behind the tunnel liner or increased concentrations of water in the concrete lining are present, the tunnel inspectors may need to use specialists with the appropriate investigative means, such as ground penetrating radar, to ascertain the full extent of such defects. In fact, one U.S. transit agency has already invested in using ground penetrating radar and laser scanning to locate deficiencies on both the area behind the liners and the inner liner surface in their concrete tunnels. These methods were supplemented with concrete cores to verify the results.

For tunnels where ground conditions or seismic events may indicate displacements in the liner, measurements should be taken as deemed appropriate to record any such deformations for historical purposes.

For tunnels with timber, a visual inspection, supplemented with cores of the timber members at critical locations, is still the most effective means of inspecting such tunnels.

For exposed rock tunnels, the geologist should carefully conduct a visual inspection of the rock and note any cracks, displacements, leaks, etc.

Mechanical/Electrical Inspection Methods

For the inspection of mechanical and electrical systems, the condition of the equipment should be documented as operational or non-operational and any observable deficiencies recorded. The mechanical and electrical inspections will only determine the operational status at the time of the inspection. Good maintenance and testing will help maintain the operational status and possibly predict failures, but this type of equipment is subject to failure without warning. The intent of the mechanical and electrical inspections is to verify that the expected maintenance has been performed and the equipment is operational through the full design range. While a rating system can be used for the mechanical systems as described above, a piece of equipment with a proposed rating of 4 (New condition) can still be subject to an equipment failure the same as a unit with a proposed rating of 2 (Fair overall condition). Specialized testing as described under *Testing* above on such equipment/systems should be maintained with other inspection results.

The degree to which the above measures are applied depend upon the scope of work as described under Mobilization above.

QC of Inspection Results

It is recommended that the tunnel owner prescribe some method of verifying that the condition ratings or other documentation of results from the inspection are indeed as presented by the inspection team, whether it be in-house staff or consultant staff. This could be accomplished in a variety of ways. First, the owner could require as part of the scope of the project that an interim inspection meeting be held where the inspection team presents their inspection findings as of the date of the meeting. If the tunnel is of such length that an interim meeting is not required, then a meeting should be scheduled upon completion of the inspection and before any reports are submitted. During this meeting, the inspection team leader(s) should briefly describe the findings, where severe deficiencies exist, where additional testing may be warranted (if not previously included in the scope), etc. If the owner is not aware of the severe deficiencies found, then it is recommended that the owner accompany the inspection team and view the severe deficiencies for such elements of the tunnel. During this field visit, the inspection team leader should also review a sampling of the condition ratings for a particular tunnel panel to explain how the various condition ratings were interpreted and applied in the field.

The tunnel owner should have the flexibility to determine the extent of the QC review based upon his knowledge of the tunnel and the degree to which he desires to rely upon the staff conducting the inspection. For specialized testing companies for mechanical and electrical systems testing, the owner may simply rely upon the certifications presented to verify that the testing agency's personnel are indeed qualified to perform the tests requested.

Documentation

The *2005 Highway and Rail Transit Tunnel Inspection Manual* required that "*the inspection should be thoroughly and accurately documented. For the tunnel structure, the documentation of severe defects should include a sketch showing the location and size of the defect and a verbal description of the defect. All severe defects should be photographed; however, a representative photo of minor or moderate defects will be sufficient.*"

The *Tunnel Inspection Manual* clearly defined the categories of defects as minor, moderate, or severe; provided priority repair definitions for critical, priority, and routine repairs; and, suggested a format for a formal report to be submitted to the tunnel owner. The formal report included the following elements:

- Letter of Transmittal
- Table of Contents
- List of Tables
- List of Figures and Drawings
- List of Photographs
- Executive Summary
- General Description
- Inspection Procedures
- Inspection Findings
- Recommendations for Repair
- Appendices (copies of specialized testing results, permits for confined space entry, structural condition rating summaries, lighting luminance level readings, etc.).

For all the above methods of inspection, it is imperative that conditions of all elements be documented and tracked over time to provide the tunnel owner with a history of element condition, repairs, etc. Although considerable structural documentation is easily created and stored through the use of hand-held pen tablet computers today, there are still many inspections documented by manually filling out field forms/sketches. It is possible to scan field forms and save them in files, which is similar to files being created directly by pen tablet computers.

In 2003 FHWA commissioned the development of a computerized Tunnel Management System (TMS) that provided a means of tracking all element conditions, repairs, costs, photos, and sketches of deficiencies and that easily generated reports for tunnel owners to use for general knowledge and for decisions regarding capital expenditures for repairs. This TMS is available directly from the FHWA free of charge for tunnel owners who desire to use such a system for tracking and maintaining tunnel conditions over time. Other tunnel owners may elect to store condition data in existing database systems, which include their bridge management systems. It is highly suggested that all tunnel owners initiate electronic storage of data collected, to facilitate easy access, even if they have not done so previously.

Separate Inspection Manuals for Highway and Rail/Transit Tunnels

Although the original intent of the FHWA/FTA in developing the TMS was to develop an inspection manual that would provide guidelines for both highway and rail transit tunnels owners, the various systems (mechanical, electrical, lighting, drainage, and security) within the tunnel are different for each of these modes, especially with regard to fire and life safety requirements. Consideration should be given to developing separate tunnel inspection guidelines for highway and rail transit tunnels, with each including the appropriate systems and elements identified for inspection.

Special Tunnel Conditions

The FHWA *Tunnel Inspection Manual* did not address special tunnel conditions such as seismic zones. Tunnel inspection guidelines should include guidance for inspections in seismic zones and submerged areas, as well as geologic considerations for rock tunnels.

Recommended Best Practices for Operational Safety/Emergency Response System Testing

As noted from the questionnaire responses presented above, a majority of tunnel owners have several items of equipment in their tunnels for both normal operations and for emergency response. These include emergency communications, fire and incident detection, emergency lighting, fire suppression equipment, drainage systems for hazardous spills, tunnel ventilation, traffic control, over-height vehicle detection systems, and pedestrian emergency egress areas. The participants from the U.S. on the scanning tour of nine European countries viewed the status of safety in European tunnels and recommended that uniform guidelines for operational safety and emergency response be developed in the U.S. in similar fashion to what Europe has done. The literature search for this project indicates that the Europeans have conducted additional research in recent years concerning human factors for both design and response during emergencies. Based on the scan tour and the advances in Europe on safety and emergency response, it would seem appropriate to recommend that best practices for operational safety/emergency response be evaluated and measures implemented in the U.S. that include the elements listed below. Accordingly, it is important that any inspection program verify that adequate systems and procedures are in place to provide a safe environment for those within a tunnel.

Inspecting and Testing for Operational Safety

As tunnels contain several crucial components and systems, it is prudent that tunnel owners maintain their systems in good working order to provide a safe environment for tunnel travelers and maintenance/operations personnel within the tunnels. It is recommended that these systems be periodically inspected during either in-depth, routine or periodic inspections, either by the tunnel owners' personnel or trained consultants, to verify the systems are in working order and will operate as expected when needed. Systems that are critical to the safe operation of the tunnel include: ventilation, CCTV cameras, lighting, signage, lane signals, over-height detections systems, drainage systems, etc. These systems should be included in the items inspected within a tunnel, and it should be verified that all systems are operational.

Specific elements to be inspected include:

- Lighting – Lighting should meet NFPA and Illuminating Engineering Society of North America requirements. Lights should be operated through all levels, and lenses should be checked for physical condition and cleanliness.
- Ventilation system – Fans should be operated at all speeds; the housing should be inspected for general cleanliness and signs of oil leakage; any maintenance performed between inspections should be reviewed; the number of hours of operation and down time should be reviewed; bearings should be observed for oil level, temperature, signs of leakage, and vibration; additional bearing testing including vibration analysis and oil sample testing can be done for a more in-depth level of investigation; and, ventilation shafts should be inspected for cleanliness and physical condition.
- CCTV cameras – Ensure the camera images are viewable on monitors at a location that is staffed by tunnel personnel and that recording equipment is operating properly.
- Signage – Signs should be inspected for the physical condition of the sign and the attachment, and the cleanliness/ability to see and read the sign.

It is also vital that tunnel operators and maintenance personnel be trained on the day to day operations of the equipment and actions to be performed to provide a safe operational environment. These operators and maintenance personnel must be knowledgeable of procedures for closing traffic lanes or completely shutting down the tunnel, de-energizing the third rail or catenary system in rail transit tunnels, general maintenance of equipment or systems, understanding of equipment malfunction, etc. By monitoring staff performance and daily staff actions, the tunnel owner can establish further training activities to ensure his tunnel(s) are being operated efficiently and that safe practices are being implemented on a daily basis. Inspections of the tunnel should also confirm that the owner has instituted safe practices for operation of the tunnel, and that the personnel are trained and regularly updated in these practices and the operation of associated equipment.

The Europeans are implementing several new safety features within their tunnels that will serve to improve operational safety. The following systems should be considered for inclusion in U.S. tunnels.

Software Linking Cameras and Automatic Incident Detection Systems

Some European tunnels have been equipped with sophisticated software that interfaces directly with video surveillance cameras and that has the capability to automatically detect, track and record incidents. A few highway tunnel owners in the U.S. have indicated that they have automatic incident detection systems; several indicated that they have CCTV cameras installed in their tunnels. Where neither of these systems is present in highway tunnels, it is recommended that the tunnel owner consider installing software-linked CCTV cameras, as a minimum, for incident detection and subsequent emergency response. If a particular tunnel has frequent incident events, it would also be prudent to evaluate the installation of an automatic incident detection system. Where it is possible to link both of these systems, the tunnel owner would have an overall system that could lead to faster detection of incidents and quicker response in the event of an emergency.

Controlling Spacing of Vehicles in Tunnels
Several tunnels in Europe have been equipped with LED lighting for safe vehicular distance (blue lights) and edge delineation of traffic lanes (white lights) in highway tunnels to provide safe distances such that a fire event has more difficulty jumping from one vehicle to another. The U.S. scanning team noted that "implementing this technology will provide the benefit of driver awareness of the roadway/tunnel limits, thus increasing (operational) safety." It seems prudent that including such measures in up to two-lane, narrow tunnels in the U.S., along with tunnel patron education, could lead to less accidents occurring within our tunnels. It should be noted that this system may not be practical in wide multi-lane tunnels.

<u>Inspecting and Testing for Emergency Response</u>
When the tunnel owner desires that a complete inspection of all tunnel elements and systems be conducted, it is recommended that all emergency response systems also be included in this inspection. However, this does not preclude testing of such systems at other regular intervals established by the tunnel owner. The inspection will verify that all equipment used during emergency events are functional and include, but is not limited to, the following systems:

- Emergency Communications – Hardwired telephones, radio and cell phone repeaters, paging systems, and motorists aid call boxes.
- Fire and Incident Detection Systems – Linear heat wire, flame detectors, spot detectors, manual fire pull stations alarms, and CCTV Cameras.
- Emergency Lighting – Integral battery pack lighting fixtures, centralized UPS, generators. It is recommended that a simulated power outage of the tunnel lighting be conducted to verify that the emergency lighting system activates and operates for a minimum of 90 minutes.
- Ventilation System – The inspection and testing for the fans as described above for operational safety.
- Emergency Egress Locations – Ensure doors are operable and cross passageways are lit and free of debris. Doors should be periodically checked for operation regularly by maintenance personnel, as the harsh environment of a tunnel accelerates door hardware deterioration and reduces the free operation of these doors.
- Fire Suppression Systems – Portable fire extinguishers have been inspected; hydrants and fire pumps are operational.
- Drainage System – Operational.
- Traffic Control – Lane signals, automatic barriers, and monitoring equipment.

Although emergency response practices in US tunnels may not include some of the safety features currently being implemented in certain European tunnels, it is believed that as these systems are expanded or implemented in the US that safety will be improved. The following example of emergency response systems utilized in Europe should be evaluated for inclusion in U.S. tunnels and inspected accordingly.

Clearly Marked Escape Routes

From visits to numerous tunnels in the U.S. and from those taking part in the scan tour in Europe, it is evident that clearly marking the escape route to the nearest exit within U.S. highway and rail transit tunnels is not common practice, as it is in many tunnels in Europe. Such a clearly marked route is necessary not only for operational safety but also for an emergency event. It is commonly understood that people are their own best rescuers during an emergency fire event and must react correctly within a few minutes in order to survive. Therefore, it is recommended that the established guidelines for emergency escape routes used in Europe be evaluated for implementation in the U.S. to achieve consistency among tunnel travelers throughout much of the world. The current standard in European tunnels consists of a mounted sign showing a white-running figure on a green background at various intervals along the tunnel wall indicating the direction to the nearest emergency exit. The European standard for this sign also includes the distance to the nearest emergency exit with white numbers on a green background under the running figure. In addition, those on the scanning tour learned through research from various European countries “that combining the use of sound that emanates from the sign, such as a sound alternating with a simple verbal message (e.g., Exit Here) with visual (and, where possible, tactile) cues makes the sign more effective. Several countries also used LED lights at emergency exit doors to aid the traveler to find the door when the tunnel is being engulfed by smoke.

Guidelines for Establishing Emergency Response Plans

It is also necessary for every tunnel owner to review current guidelines or establish clear guidelines, if none exist, for emergency response actions during potential emergency events. Although an owner may not be under the jurisdiction of NFPA 502, Chapter 12 of NFPA 502 does provide guidelines for suggested emergency events to be included in an emergency response plan and participating agencies that may need to be included in the plan. It is suggested that different plans be initiated for different events as different equipment and personnel actions are required for the different events. These emergency response plans should incorporate all potential equipment, i.e. ventilation, electrical, lighting, that will be effected by the event and actions to be taken by tunnel personnel. A listing of all agencies (fire, police, hazard materials, emergency medical, utilities, media, and others deemed necessary) shall be included for immediate contact. A detailed listing of procedures in the order to be followed should be readily accessible by hard copy and on a computer such that emergency responses can be initiated as quickly as possible and specific agency personnel, such as fire, police and emergency medical technicians (EMT’s), need to be included in periodic drills to train and reinforce the emergency procedures so that they become second nature to the personnel.

Depending upon the current sophistication of computer software within the tunnel agency, some of these actions for the emergency event may be automatically set in motion by the computerized software. As technology improves in the future, highway tunnel owners should consider automating as many of these processes as possible. This would be similar to the one-button system employed in the long Mont Blanc Tunnel between France and Italy where several lives have previously been lost due to emergency fire events. Those participating in the scan toured stated that “the one-button system initiates several critical actions without giving the operator the chance to omit an important step or perform an action out of order”.

Respondents to the questionnaire indicated that they test their emergency response procedures at intervals of 6 months, 12 months, and 24 months, with a majority occurring every 12 months. NFPA 502 indicates that training for tunnels on limited access highways should occur every 6 months. If tunnel owners are not under the jurisdiction of NFPA 502, they should at least consider conducting emergency systems testing on an annual basis to validate that personnel are trained for emergency events. The times for tunnel closure, in order for the various agency respondents to practice for a planned emergency, should be dictated by the tunnel owner based upon traffic volumes through the tunnel, whether vehicles or trains. Depending upon the results of the training, the owner can establish additional training to offset weaknesses observed during the practice event. By continuing these testing events with new personnel on a regular basis to be determined by the tunnel owner, the tunnel operators are more likely to be prepared to respond more quickly to emergency events.

Tunnel inspections should confirm that emergency response plans, with the elements indicated above, exist, are documented, and that personnel are trained and rehearse emergency response procedures on a regular basis.

Inventory Data Format

With the development of the National Tunnel Management System (NTMS) in 2003, Gannett Fleming, Inc. (Gannett Fleming) gathered inventory data from both highway and rail transit tunnel owners across the country to complete the first ever national inventory of tunnels. The data gathered from 39 out of 45 highway tunnel owners and 21 out of 26 rail transit tunnel owners included the following data fields:

a. Highway Tunnels
    - State
    - Owner
    - Contact Name
    - Tunnel Name
    - Highway Route Number
    - Year Constructed
    - Overall Tunnel Width (feet) – Although only one data field is shown here, the author is fully aware that some tunnels have entrance/exit ramps within the tunnels where the width of the tunnel can vary along its length. For these cases, it would be best for the inspector to break up the tunnel into segments that describe the width of the tunnel sufficiently such that the information in the database accurately depicts conditions for the entire tunnel length.
    - Tunnel Length (feet) – If multiple segments are needed to describe the tunnel, this field would apply to a particular segment.
    - Vertical Roadway Clearance (feet) – If multiple vertical clearances exist within the tunnel, then multiple segments are needed to clearly define the tunnel.

Horizontal Roadway Clearance (feet) – Where transitions in width occur within the tunnel, multiple segments are required to clearly define the tunnel.

Construction Method – Some tunnels contain multiple versions of these methods and should be broken into appropriate segments accordingly.

- Cut and Cover
- Shield Driven
- Bored
- Drill and Blast
- Sequential Excavation Method (NATM)
- Unknown

Tunnel Shape - Some tunnels contain multiple shapes and should be broken into appropriate segments accordingly.

- Circular
- Rectangular
- Horseshoe
- Oval/Egg
- Other

Construction Ground Conditions – Some tunnels contain multiple ground conditions and should be broken into appropriate segments accordingly.

- Soft Ground
- Mixed Face
- Rock
- Other

Lining and Support – Some tunnels contain multiple types of linings and should be broken into appropriate segments accordingly.

- Unlined Rock
- Cast in Place Concrete (No Reinforcement)
- Cast in Place Concrete (Reinforced)
- Shotcrete/Gunite
- Precast Concrete Liner Segments
- Steel/Iron Liner Plate
- Masonry
- Other

Ventilation System Type

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

Mechanical Ventilation

- Tunnel Mounted
- Portal Building
- Ventilation Building not at Portal
- No Mechanical Ventilation (Natural)

Lighting

- Fluorescent

High Pressure Sodium
Low Pressure Sodium
Metal Halide
Pipe Lighting
None

b. <u>Rail Transit Tunnels</u>

State
Agency Acronym (such as Bay Area Rapid Transit (BART))
Owner/Agency (such as BART)
Contact Name
Tunnel Name
Segment or Line
Year Constructed (Range for Line)
Overall Tunnel Height (feet)
Overall Tunnel Width (feet) - Although only one data field is shown here, the author is fully aware that some tunnels have entrance/exit ramps within the tunnels where the width of the tunnel can vary along its length. For these cases, it would be best for the inspector to break up the tunnel into segments that describe the width of the tunnel sufficiently such that the information in the database accurately depicts conditions for the entire tunnel length.
Tunnel Length (feet) - – If multiple segments are needed to describe the tunnel, this field would apply to a particular segment.
Construction Method - Some tunnels contain multiple versions of these methods and should be broken into appropriate segments accordingly.

- Cut and Cover
- Shield Driven
- Bored
- Drill and Blast
- Immersed Tube
- Sequential Excavation Method (NATM)
- Other

Tunnel Shape

- Circular
- Rectangular
- Horseshoe
- Oval/Egg
- Other

Construction Ground Conditions

- Soft Ground
- Mixed Face
- Rock
- Other

Lining and Support

- Unlined Rock
- Cast in Place Concrete (No Reinforcement)

- Cast in Place Concrete (Reinforced)
- Shotcrete/Gunite
- Precast Concrete Liner Segments
- Steel/Iron Liner Plate
- Masonry
- Other

Ventilation System Type
- Longitudinal
- Semi-Transverse
- Full Transverse
- Single Point Extraction
- Natural

Mechanical Ventilation
- Tunnel Mounted
- Portal Building
- Ventilation Building not at Portal
- No Mechanical Ventilation
- Other

c. Potential Additional Inventory Data Fields to be included:

For highway tunnels, it is realistic to provide certain inventory and roadway specific information that tunnel owners may desire to include in their tunnel reporting. This would include items that FHWA requires for "Under" records in the National Bridge Inventory, especially those that provide more precise geometric, clearance and roadway system data. By doing this, the tunnel inventory system can be seamlessly merged with the National Bridge Inventory (NBI) to provide consistent geometric and emergency planning information to FHWA, which was the first intent of the NBI. For example, the detour/bypass length is necessary if a tunnel cannot be used to emergency access an area or if the emergency vehicles cannot fit physically within the tunnel. Likewise the roadway system functional classification, the Inventory Route Coding for Item 5 in the NBI, Strategic Highway Network (STRAHNET), National Highway System (NHS), etc. are vital for strategic planners in identification of tunnels for emergency routes being studied.

Admittedly, not all of the items that are required for "Under" records are applicable to tunnels, as they in reality assume that the inventory route is going under a bridge. Nevertheless, FHWA will need to identify those items that are indeed vital to emergency route planning.

- In concert with "Under" inventory data, the following additional inventory data fields should be provided as a minimum:
- Traffic
  - Annual Average Daily Traffic
  - Annual Average Daily Truck Traffic

- Finishes
    - Tiles
    - Concrete-filled Metal Panels (Ceiling)
    - Metal Panels (Walls)
    - Precast Concrete Panels (Ceiling)
    - Precast Concrete Panels (Walls)
    - Paint
    - None
    - Other
- Number of "tubes"
- Number of lanes per "tube"
- Sidewalks
    - Yes
    - No
- Emergency System Inventory
    - Fire Detection, Fire Suppression, Chemical Hazard Detection
        - Linear Heat Wire
        - Flame Detector
        - Spot Detectors
        - Manual Pull Stations
        - Hazardous Material Spill/Gas Detection
        - Portable Fire Extinguishers
        - Fire Department Hose Connections
        - Hydrants
        - Water Supply Source
            - Public or Private
        - Fire Pump
            - Electric or Diesel
        - Fixed Fire Suppression Systems
            - Sprinklers or Deluge
    - Emergency Lighting/Power
        - Integral Battery Pack Lighting Fixtures
        - Centralized Uninterruptible Power Supply
        - Generator (Fuel Type: Diesel, Natural Gas, Propane)
        - Dual-Utility Service
    - Traffic Control/Monitoring
        - Lane Signals
        - Portal Mounted and/or within Tunnel
        - Closed Circuit Television Cameras
        - Outside and/or within Tunnel
    - Pedestrian Egress
        - Exit Path Signage
        - Emergency Exists within 1,000 feet of any point in tunnel
        - Safe Rooms
    - Cross Passageways

    - Communications
        - Hardwired Telephones
        - Radio and Cell Phone Repeaters
- Portal Buildings
    - Yes
    - No
- Traffic Operations Center
    - Yes
    - No

For Rail Transit tunnels, the following additional inventory data fields are recommended:

- Power
    - Third Rail
    - Catenary
    - Other
- Number of Tracks
- Emergency Exits
    - Yes
        - Spacing ____________(feet)
    - No

<u>Tunnel Data Fields</u>

For the condition of tunnel assets to be tracked over time, and to facilitate comparison of tunnel conditions between multiple tunnels, a standard set of data fields should be established for all inspectors to complete on each inspection. Suggested data fields were provided by Gannett Fleming during the development of the NTMS in 2003. However, the TMS was designed such that additional fields could easily be added by any tunnel owner based upon their particular tunnel assets.

a. The TMS currently contains the following suggested data fields for tracking the condition of tunnel assets. These fields are used to document the condition of individual elements (such as a tunnel panel), as well as the overall tunnel.
    - Underside of tunnel arch
    - Ceiling slab topside
    - Ceiling slab underside
    - Ceiling hangers
    - North wall
    - South wall
    - East wall
    - West wall
    - Inner wall
    - Outer wall

- North facade
- South facade
- East facade
- West facade
- Column
- Portal buildings
- Sidewalk
- Railings
- Cross passageways
- Drainage
- Floor slab
- Lighting fixtures
- CCTV cameras
- Sump pit
- Beams
- Deluge system
- Fire alarm system
- Emergency telephone
- Ramp

There is no limit to the number of elements to be tracked for the inspection; additional data fields can be added, as necessary, depending upon the elements existing within a particular tunnel.

b. Potential Additional Condition Data Fields to be Considered by Tunnel Owners

- Retaining walls
- Slope stability – whereas the slopes above the tunnel are not part of the tunnel structure, they can play a part in overall tunnel safety depending upon their proximity to the tunnel portal. If a condition rating is to be assigned, the tunnel owner should define the various criteria for the rating categories.
- Fans
- Ventilation ducts and shafts
- CO system
- Fire extinguishers
- Emergency generator
- Duct bank
- Track bed
- Track

Conclusion

It is clear from the literature search that inspections of highway and rail transit tunnels are generally occurring in some fashion throughout the U.S. by DOTs, agencies, and other tunnel owners. It is anticipated that FHWA will issue National Tunnel Inspection Standards on tunnel inventory and element condition reporting in 2010 that will most likely be more stringent than current reporting of tunnel information within the bridge SI&A forms. Since there is currently no consistency in the tunnel inspection techniques used by the various tunnel owners, implementing NTIS and developing a tunnel inspector training program on applying those standards will be vital to ensuring a consistent tunnel inspection program for all tunnels across the nation. In anticipation of the upcoming increased federal involvement in tunnel inspections and reporting, these best practices for tunnel inspections and operational safety/emergency response systems testing, as presented in this report, may be used by tunnel owners to improve the physical inspections as well as the documentation and quality of the inspection results.