Tunnel Operations, Maintenance, Inspection, and Evaluation Manual: Evaluation

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Gilbert Gedeon, P.E.

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.ca

This course was adapted from the Federal Highway Administration (FHWA) agency of the Department of Transportation, document "Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual – Chapter 5: Evaluation", which is in the public domain.

TOMIE MANUAL

CHAPTER 5

EVALUATION

Chapter 5 - Evaluation

5 Evaluation

The cost of maintaining and improving tunnel systems must be balanced against the amount of available funding. Resources are limited for making repairs and upgrades; therefore, repairs need to be evaluated and prioritized to make informed investment decisions.

Evaluations are normally performed after the inspection data is received. Sound engineering judgment is used to evaluate the consequences of tunnel system or component failure in terms of overall safety, service level, and costs. In some instances, supplementary inspections and testing may be needed where data is lacking. Risk assessment techniques should include strategies for deploying, operating, maintaining, upgrading, and disposing of tunnel system components in a cost-effective manner.

When a structural system within the tunnel supports vehicular live loads, a load rating must be performed in accordance with the National Tunnel Inspection Standards (NTIS). The results of the load rating may be used to determine the need for a load posting, or the rating may be used to issue a hauling permit.

This chapter focuses on the evaluation of tunnel systems and components to include the typical personnel involved, supplemental inspection and testing methods, risk-based assessments, priority classification, and basic cost estimating. Information is also provided on load rating.

5.1 Qualifications of Personnel

The program manager and team leader should be included in the evaluation team. If the tunnel systems are complex, it may be advisable to use qualified specialists, specialty contractors, or consultants to augment the evaluation process. The evaluation team should have a thorough understanding of the tunnel facility including operations, maintenance, inspection, design, cost estimating, scheduling, construction, and rehabilitation.

The tunnel owner should establish the qualifications necessary for evaluating various tunnel systems and components to include criteria for education, training, experience, and certification or professional registration. The qualifications of the evaluation team should commensurate with the written policies and procedures for tunnel inspection. In accordance with the NTIS, *the load rating of a tunnel must be performed by a professional engineer*. A professional engineer is typically characterized as an individual who has fulfilled specific education and experience requirements and passed certain examinations that permit the person to provide appropriate engineering services within a jurisdiction in accordance with all applicable laws.

5.2 Supplemental Inspections and Testing

Sometimes additional information is needed after an inspection to complete an evaluation; or additional data may be needed to further define a particular deficiency, the sectional properties of an element, or the engineering properties of a material. In-depth and special inspections, as defined in Chapter 4 of this manual, are often used to obtain additional information during the evaluation process. There are also several field test and laboratory techniques for evaluating material properties.

5.2.1 Nondestructive Test Methods

NDT methods are useful for a variety of purposes ranging from verifying the tunnel geometry to identify temperature differences. Additional nondestructive testing (NDT) methods generally used with tunnels include:

- Air-coupled GPR
- Infrared thermography
- Scanners
- Ground-coupled GPR
- Ultrasonic tomography
- Ultrasonic echo
- Ultrasonic surface waves
- Impact echo

Information on non-destructive testing can be found at:

http://www.ndtoolbox.org/content/tunnels

The limitations of these technologies should be considered prior to implementing them. The techniques typically produce reasonable results when the defects are at least 1 square foot and located at depths less than 4 inches below the surface.

NDT technologies are used to better characterize the extent of deficiencies in structural elements below the surface. Baseline readings should be obtained on critical elements to monitor defects and rate of decline. NDT methods generally require specialized and proprietary equipment purchased from a vendor. With respect to highway tunnel applications, various NDT methods can be used to evaluate:

- Water leakage.
- Delamination and spalling of concrete liners.
- Voids behind and within tunnel linings.
- Concrete permeability.
- Tiles that are in the process of separating from the tunnel liner.
- Integrity of concrete covered steel liners.
- Integrity of ceiling systems and connections with the tunnel lining.

5.2.2 Field Test Methods

The AASHTO Manual for Bridge Evaluation (MBE) discusses various field tests for concrete, steel, and timber. The field tests for concrete include strength methods, sonic methods, ultrasonic techniques, magnetic methods, electrical methods, nuclear methods, thermography, radar, radiography, and endoscopes. The field tests for steel include radiography, magnetic particle examination, eddy current examination, dye penetrant examination, and ultrasonic examination. The field tests for timber include penetration methods, electrical methods, and ultrasonic examination. In addition, it may be necessary to perform field tests on the geological and geotechnical materials in the vicinity of the tunnel. Some of the common ASTM field test methods for rock and soil are listed in Tables 5.1 and 5.2.

Table 5.1 – Field Tests for Geological (Rock) Materials

Test Designation	Title of Test
ASTM D 4435	Method for Rock Bolt Anchor Pull Test
ASTM D 4436	Method for Rock Bolt Long-Term Load Retention Test
ASTM D 4553	Method for Determining In Situ Creep Characteristics of Rock
ASTM D 4554	Method for In Situ Determination of Direct Shear Strength of Rock Discontinuities
ASTM D 4623	Method for Determination of In Situ Stress in Rock Mass by Overcoring Method—USBM Borehole Deformation Gauge
ASTM D 4729	Method for In Situ Stress and Modulus of Deformation Using Flatjack Method

Table 5.2 – Field Tests for Geotechnical (Soil) Materials

Test Designation	Title of Test
ASTM D 2573	Method for Field Vane Shear Test in Cohesive Soil
ASTM D 4044	Method for (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers
ASTM D4050	Method for (Field Procedure) for Withdrawal and Injection Well Testing for Determining Hydraulic Properties of Aquifer Systems

5.2.3 **Laboratory Test Methods**

The MBE discusses various laboratory tests methods for concrete, steel, and timber. Table 5.3 and 5.4 list the ASTM standards that are commonly used for laboratory testing of geological (rock) and geotechnical (soil) materials. Laboratory tests should be conducted by facilities that meet the requirements established in the respective standards.

Table 5.3 – Laboratory Tests for Geological (Rock) Materials

Test Designation[(1)]	**Title of Test**
D2936	Method for Direct Tensile Strength of Intact Rock Core Specimens
D 3967	Method for Splitting Tensile Strength of Intact Rock Core Specimens
D 4535	Methods for Measurement of Thermal Expansion of Rock Using Dilatometer
D 4644	Method for Slake Durability of Shales and Similar Weak Rocks
D 5607	Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force
D 5731	Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications
D 5873	Method for Determination of Rock Hardness by Rebound Hammer Method
D 6032	Method for Determining Rock Quality Designation (RQD) of Rock Core
D 7012	Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures
D 7070	Methods for Creep of Rock Core Under Constant Stress and Temperature
D 7401	Methods for Laboratory Determination of Rock Anchor Capacities by Pull and Drop Tests
D 7625	Method for Laboratory Determination of Abrasiveness of Rock Using the CERCHAR Method

Table 5.4 – Laboratory Tests for Geotechnical (Soil) Materials

Test Designation[(1)]	**Title of Test**
D 422	Method for Particle-Size Analysis of Soils
D 2166	Method for Unconfined Compressive Strength of Cohesive Soil
D 2216	Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D 2435	Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading
D 2850	Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils
D 3080	Method for Direct Shear Test of Soils Under Consolidated Drained Conditions
D 4318	Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
D 4546	Methods for One-Dimensional Swell or Collapse of Soils
D 4648	Method for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil
D 4829	Method for Expansion Index of Soils
D6913	Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis
D 7263	Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens

5.3 Evaluation of Tunnels

Inspection findings are used to determine if there are safety and structural concerns. Tunnel systems provide a certain level of safety and enhance service; the criticality of the component should be evaluated for safety, service, and cost implications. Evaluations are used to prioritize repairs and to make informed investment decisions. A data-driven, risk-based approach can be used to achieve optimized performance. Repair decisions are focused on costs and funding availability; as such, a cost estimate is an important part of the evaluation process. Sound engineering judgment is needed to arrive at meaningful conclusions.

5.3.1 **Evaluation Strategies**

Components of tunnel evaluation strategies include risk assessment, priority classification, cost estimating, life cycle prediction, and asset management. The scope and depth of an evaluation will vary depending on the complexity and sophistication of the tunnel. Tunnel evaluation programs are developed to suit the overall needs of the tunnel owner.

5.3.1.1 **Risk-Assessment**

Risk assessment is intended to provide a cost effective approach to decision-making based on analysis of data. Risks are evaluated using various qualitative or quantitative techniques, and the consequences of component or system failure are considered. Consequences are evaluated for safety, security, service level, and cost. A risk register is a common tool that is used for identifying risks. Evaluation helps to prioritize repairs and optimize resources as part of an effective tunnel management approach.

5.3.1.2 **Priority Classification**

Priority classification is performed as part of the inspection process to ensure that conditions discovered during an inspection get the proper rating. Similarly, evaluations should include a priority classification scheme that supports the management approach. An example priority classifications scheme is described below:

Critical Finding – A defect or deficiency that requires immediate action as defined in the NTIS.

Priority Repair – These repairs will improve the durability, reliability, aesthetics, or functional capability of the tunnel system and will reduce future maintenance costs. Elements that no longer comply with code requirements might also be included in this classification depending on the policies of the tunnel owner. These repairs typically require quality checking to ensure adequate performance and are generally scheduled for repair prior to the next inspection cycle.

Routine Repair – These repairs are part of not as critical to the safety and performance of the tunnel structure and can be repaired when more budget is available or as part of a routine maintenance program. These repairs are typically completed when the schedule permits.

Figure 5.1 depicts an optimized replacement plan for an off-the-shelf pump motor deemed to have minimal consequence of failure. Figure 5.2 depicts an optimized preventative maintenance schedule for a customized fan motor deemed to have a high consequence of failure.

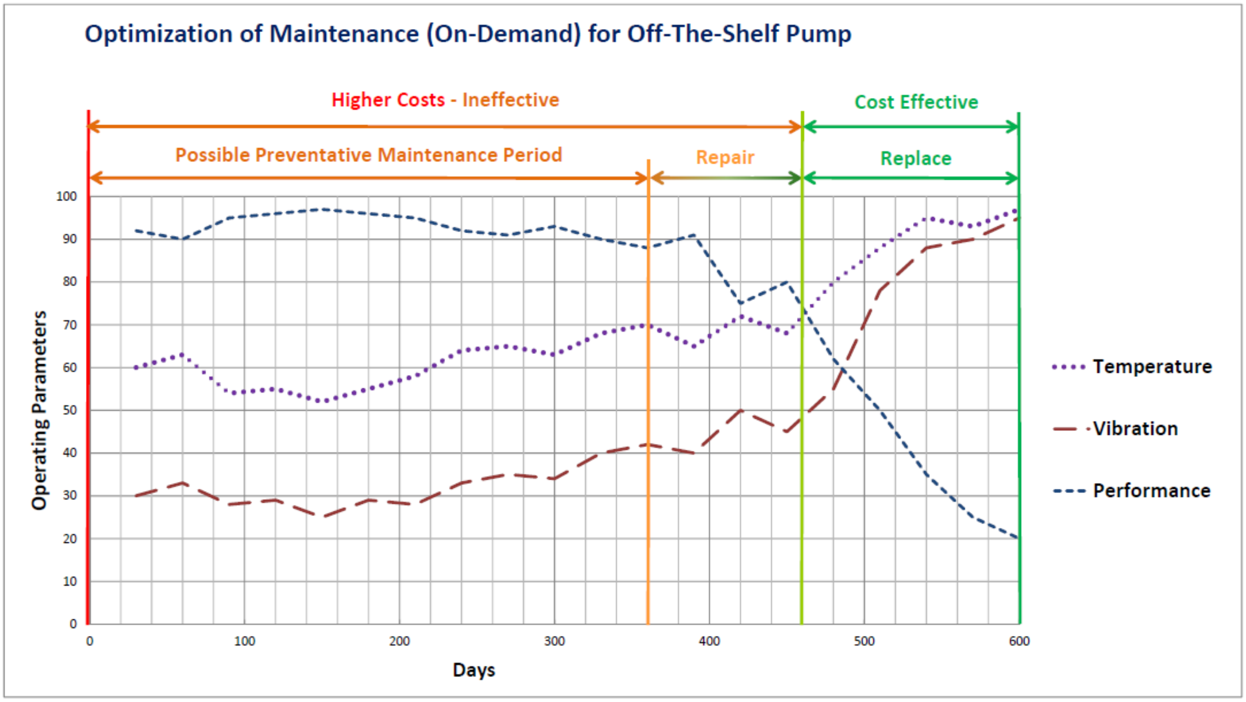

Figure 5.1 – Optimized on-demand maintenance for an off-the-shelf pump.

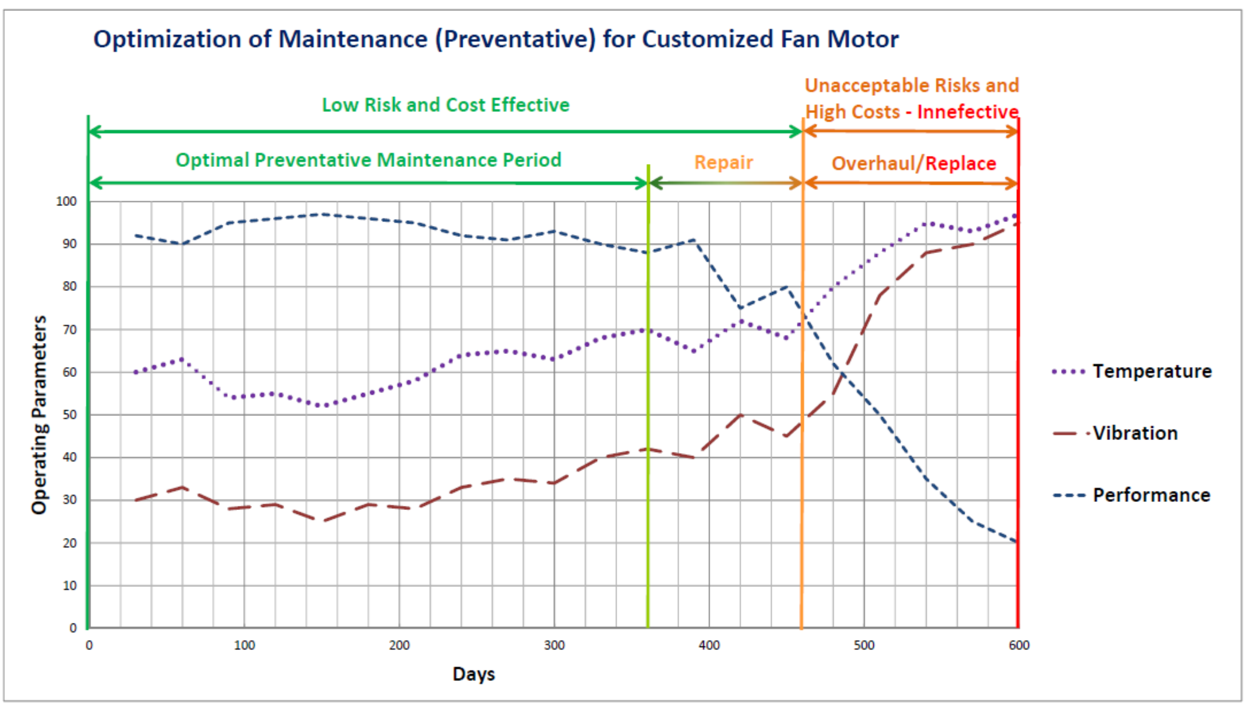

Figure 5.2 – Optimized preventative maintenance schedule for a customized motor.

5.3.1.3 **Cost Estimating**

A cost estimate is usually needed as part of the evaluation process to successfully manage and budget for repairs. Alternative repair schemes also need cost estimates for comparison purposes. Repair costs are influenced by a number of considerations. For evaluation purposes, a sufficient cost estimate can generally be made using methods discussed in AASHTO 2013. This guide identifies four key estimating techniques to include:

- Conceptual estimating
- Bid-based estimating
- Cost-based estimating
- Risk-based estimating

Based on the estimated quantities of labor, materials, and equipment and meaningful consideration of incidental items, such as mobilization of equipment, traffic maintenance, contingency, subcontractor fees, and contractor overhead and profit, sufficient cost estimates can be made for evaluation purposes. If the repair scheme involves work at a future date, then the time value of money must be taken into account.

Table 5.5 shows a very simple example of a cost estimate that compares two different repair schemes where the amount of repair work does not change over the repair period. This simple example indicates that if funds are limited in any particular year, then there is not a significant difference when the repairs are performed. In other cases, the cost and amount of repair work could significantly increase because of inflation and the neglected repairs could increase the rate of deterioration and require more extensive repairs.

5.3.1.4 **Life-Cycle Costs**

Life cycles are estimated using relevant deterioration models based on data collected over many inspection cycles. Cost effective strategies consider the costs of various competing alternatives over a specific duration or time period such as the remaining useful life of a particular tunnel system, the next ten years, etc. Life-cycle analysis is a useful tool for evaluating capital investment alternatives such as whether to purchase, own, operate, maintain, or replace an asset. For example when considering obsolete fan systems, it might require less up-front capital to overhaul the motors than purchase new motors; however, the new fan motors may last longer, consume less power, and require less maintenance expenditures, which over the useful life cycle could cost less. If the new controllers are compatible with the planned supervisory control and data acquisition system, then these benefits should also be included in the evaluation.

5.3.1.5 **Asset Management**

Asset management involves deploying, operating, maintaining, upgrading, and replacing tunnel system components in a cost-efficient manner while maintaining acceptable levels of safety and service. These schemes evaluate alternatives and determine the most effective use of limited resources by employing optimized allocation techniques.

Table 5.5 – Sample simple cost estimate for comparing two alternative repair schemes.

Item		Repair	Labor		Material		Equipment		Costs	
			Quantity	Unit Cost	Quantity	Unit Cost	Quantity	Unit Cost	Time Value of Money i=6%	Dollars
			Hours	$/Hour	yd^3 (Cubic Yards)	$\$/yd^3$	Days	$/Day		
ALT 1	**Year 1**	Voids	60	55.00	300	175.00	8	500.00	-	59,800
		Cracks	20	25.00	10	75.00	3	50.00	-	1,400
		Etc.	-	-	-	-	-	-	-	
		Total								61,200 + …
	Year 3	Voids	10	55.00	50	175.00	2	500.00	1,275	11,575
		Cracks	5	25.00	3	75.00	1	50.00	50	450
		Etc.	-	-	-	-	-	-	N x 1.06^2	
		Total								12,025 + …
	Total									73,225
ALT 2	**Year 1**	Voids	30	55.00	150	175.00	4	500.00	-	29,900
		Cracks	10	25.00	5	75.00	2	50.00	-	725
		Etc.	-	-	-	-	-	-	-	
		Total								30,625 + …
	Year 3	Voids	40	55.00	200	175.00	5	500.00	4,900	44,605
		Cracks	15	25.00	8	75.00	2	50.00	135	1,210
		Etc.	-	-	-	-	-	-	N x 1.06^2	
		Total								45,815 + …
	Total									76,440

5.3.2 Civil and Structural Evaluations

When establishing the conditions of the tunnel and evaluating the engineering properties of the materials, it is important to have the existing records available to obtain the appropriate design, construction, and maintenance information. The geotechnical records should also be reviewed to obtain the soil parameters and the groundwater information. This information may be useful for example when assessing a leaking segment of the tunnel or where the geometry of the tunnel cross-section changes. If any essential information is missing, special or in-depth inspections can be used to obtain the missing information.

Table 5.6 – Sample simple ranking for repair of a civil or structural component.

Ranking	Repair	Structure Condition	Risk	Priority	Costs		Effectiveness		Remarks
					Alt 1	Alt2	Alt 1	Alt2	
1	Replace Ceiling Slab and Girders	Severe	High	Priority	1,750,000	2,250,000	+$750,000	+$0	Plenum ice => overload. Now temp supported
2	Patch Interior Wall and Tile	Poor	Moderate	Routine	$50,000	$75,000	+$40,000	+$5,000	Concrete spalls + tile observed on roadway
…..	…..	…..	…..	…..		…..		…..	..

A table can be set up as a tool for evaluating civil and structural elements based on the basic evaluation schemes that were previously discussed. From Table 5.6 for example, qualitative evaluations can be used to rank repairs. The evaluation method developed should be based on the policies and practices of the tunnel owner. More elaborate quantitative methods can be developed to take advantage of multi-variable codified input parameters using sophisticated algorithms processed by computer software; however, it is highly recommended to use engineering judgment as a final check for evaluating quantitative results.

Structural Analysis – It is important to evaluate the changes that might impact the load carrying capacity and durability of civil and structural elements. The primary considerations include material degradation and section loss. Loads may have changed over time due to a number of factors such as the installation of new equipment, heavier truck use, earthwork, and changing groundwater levels. The evaluation should consider the pertinent assumptions used in the design to include any standards, codes, or criteria that were used. A structural analysis should be performed on a structure that supports loads in the tunnel when there are changes to:

- The loads supported by the tunnel structure.
- Section loss occurs in the structure.
- The material properties are degraded due to corrosion and deterioration.

The ground interacts with the tunnel liner rather than simply acting as an applied load on the final liner. The ground should be treated as a material with engineering properties to include strength, stiffness, and weight. The ground may also distribute all or a portion of the live loads in the vicinity of the tunnel. If a highway tunnel supports live loads from aircraft or rail vehicles, it would be prudent to conduct a structural analysis of the tunnel liner.

5.3.3 Evaluation of Functional Systems

Functional systems are comprised of various components that provide essential services such as ventilation, pumping, flood protection, heating, cooling, distribution of power, emergency power generation, lighting, fire detection, fire protection, communication, and surveillance. When evaluating functional systems, it is also important to obtain the design, construction, and maintenance records to establish the configuration and as-built conditions of the functional system components. Schematics, diagrams, and schedules provide important information about the interworking of these systems; the evaluation team should understand them; and it is common to employ qualified specialists, specialty contractors, and consultants when evaluating functional systems.

Functional systems can be complex with interdependent components that are shared between different tunnel systems. Some components may be redundant, and complete failure of one item may not prevent the system as a whole from functioning as intended. Other components may lack redundancy, and their failure could result in partial or total system failure. It is also important to review the standards, codes, and the criteria that are referenced in the project records.

A table can be helpful for evaluating functional systems. For example, Table 5.7 presents a simple ranking scheme that may be useful for making repair decisions. The evaluation method developed should be based on the policies and practices of the tunnel owner. More elaborate quantitative methods should be developed, as needed, to take advantage of more sophisticated computer algorithms if they are available; however, it is highly recommended that engineering judgment be used to evaluate all of the results.

Table 5.7 – Example of a simple ranking for repair or replacement of a functional system.

Ranking	Repair	Structure Condition	Risk	Priority	Costs		Effectiveness		Remarks
					Alt 1	Alt2	Alt 1	Alt2	
1	Replace Ceiling Slab and Girders	Severe	High	Priority	1,750,000	2,250,000	+$750,000	+$0	Plenum ice => overload. Now temp supported
2	Patch Interior Wall and Tile	Poor	Moderate	Routine	$50,000	$75,000	+$40,000	+$5,000	Concrete spalls + tile observed on roadway
…..	…..	…..	…..	…..		…..		…..	..

5.3.3.1 **Mechanical systems**

Mechanical systems include the fan and ventilation system, drainage system and pumps, the emergency generator, flood gates, and other such components. The requirements for mechanical systems are generally established by State and local authorities that adopt provisions from building codes, standards, or design guides. The requirements for each tunnel should be established in the file records. If the file records indicate that, for example, a particular mechanical system was designed to meet the requirements of the International Mechanical Code of the International Code Council (2015 Edition) or the Unified Plumbing Code of International Association of Plumbing and Mechanical Officials (2012 Edition), then these references serve as a basis for establishing the minimum requirements for the mechanical components, as applicable.

Figures 5.3 through 5.5 illustrate the type of information that should be understood when evaluating functional systems such as flow diagrams, fan schedules, and wiring diagrams. When evaluating components of mechanical system, the effects of an element on the system as a whole must be understood. For example:

- Is the component redundant within the system?
- Is the component only for boosting normal operating capacity during peak travel?
- Is the component needed for mitigating emergency conditions?
- Is the component needed to satisfy the required redundancy levels?

Ventilation system – The ventilation system dilutes vehicle fumes and exchanges the air during normal operations; during fires, these systems are used to control the smoke, pressurize escape routes, and exhaust dangerous fumes and superheated gasses from the tunnel. Ventilation systems may include the following subcomponents: fans, airways, sound attenuators, dampers, damper motor, damper controller, air quality monitoring equipment such as for carbon monoxide (CO), control panels and conduit.

Drainage and pumping system – These elements may include storm drains, piping, pumps and water treatment equipment. The drainage and pumping system may include various subcomponents such as motors and controllers.

Emergency generator system – The elements of this system include the mechanical components of the emergency generator such as fuel delivery pumps, fuel storage, engine components, engine cooling system, and exhaust components. The emergency generator system may include the following subcomponents: main fuel storage tank, day fuel tanks, circulating fuel pumps, fuel tank ventilation, fuel tank sensors, cooling systems, exhaust manifold, insulation, exhaust air louver and damper actuator, supply air louver and damper actuator, generator, generator control equipment, control panels, and associated conduit.

Flood gates – Flood gates generally include seals, mechanical components, hydraulic systems, and power supply equipment.

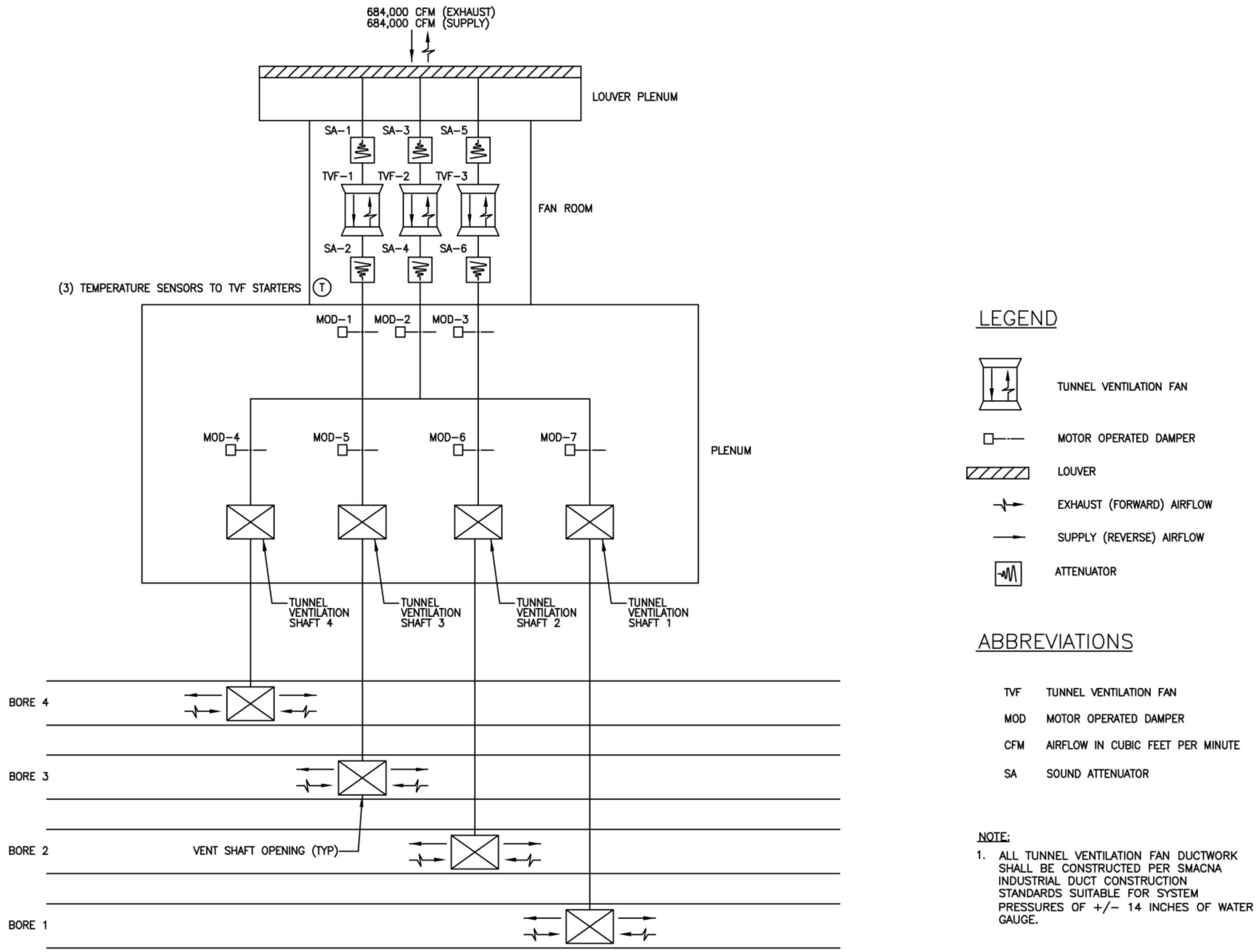

Figure 5.3 – Sample tunnel ventilation air flow diagram.

TUNNEL VENTILATION FAN SCHEDULE

FAN NO.	LOCATION	FAN DATA			FAN MOTOR DATA					MAXIMUM FAN SOUND POWER LEVELS (dB re 10^{-12} WATTS)								REMARKS
		AIR QUANTITY (CFM)	TOTAL PRESS. (IN. W.G.)	NOMINAL FAN DIA. (INCHES)	MAXIMUM NAMEPLATE HP	RPM	VOLTS	PHASE	HERTZ	63 HZ	125 HZ	250 HZ	500 HZ	1K HZ	2K HZ	4K HZ	8K HZ	
TVF-1	FAN ROOM	228,000	5.60	96	350	1,200/600	460	3	60	111	116	126	129	125	121	117	114	SEE NOTES 1, 2 AND 3.
TVF-2	FAN ROOM	228,000	5.60	96	350	1,200/600	460	3	60	111	116	126	129	125	121	117	114	SEE NOTES 1, 2 AND 3.
TVF-3	FAN ROOM	228,000	5.60	96	350	1,200/600	460	3	60	111	116	126	129	125	121	117	114	SEE NOTES 1, 2 AND 3.

NOTES:
1. THE INDICATED AIRFLOW CAPACITY AND TOTAL PRESSURE REQUIREMENTS FOR TUNNEL VENTILATION FANS APPLY TO FAN OPERATION IN FORWARD (EXHAUST) MODE. THE REQUIRED AIRFLOW CAPACITY AND TOTAL PRESSURE FOR REVERSE (SUPPLY) MODE IS 228,000 CFM AT 5.40 IN. W.G.
2. FAN PERFORMANCE DATA INDICATED IS BASED ON AIR DENSITY OF 0.085 POUNDS PER CUBIC FOOT.
3. MOTOR HORSEPOWER SHALL NOT EXCEED 350.
4. SEE NOTES 3 TO 5 OF ATTENUATOR SCHEDULE.

TUNNEL VENTILATION MOTOR OPERATED DAMPER SCHEDULE

DAMPER NO.	LOCATION	FRAME MOUNTING PLANE	CLEAR OPENING INSIDE DAMPER (FT–IN.)		NUMBER OF EQUAL MODULES	DAMPER MOTOR OPERATOR								REMARKS
						MOTOR DATA				MIN. NO. OF MOTOR OPERATORS	DE–ENERGIZED DAMPER POSITION	MOTOR LOCATION		
			"A"	"B"		MAX. HP	VOLTS	PHASE	HERTZ			IN AIR STREAM	SIDE–MOUNTED	
MOD–1	FAN PLENUM	VERTICAL	10'–0"	12'–0"	2	1/3	120	1	60	2	OPEN	X	–	SEE NOTE 1.
MOD–2	FAN PLENUM	VERTICAL	10'–0"	12'–0"	2	1/3	120	1	60	2	OPEN	X	–	SEE NOTE 1.
MOD–3	FAN PLENUM	VERTICAL	10'–0"	12'–0"	2	1/3	120	1	60	2	OPEN	X	–	SEE NOTE 1.
MOD–4	FAN PLENUM	HORIZONTAL	16'–0"	18'–0"	8	1/3	120	1	60	4	OPEN	X	–	SEE NOTE 1.
MOD–5	FAN PLENUM	HORIZONTAL	16'–0"	18'–0"	8	1/3	120	1	60	4	OPEN	X	–	SEE NOTE 1.
MOD–6	FAN PLENUM	HORIZONTAL	16'–0"	18'–0"	8	1/3	120	1	60	4	OPEN	X	–	SEE NOTE 1.
MOD–7	FAN PLENUM	HORIZONTAL	16'–0"	18'–0"	8	1/3	120	1	60	4	OPEN	X	–	SEE NOTE 1.

NOTE:
1. DAMPER ACTUATORS SHALL BE OF THE ALL–ELECTRIC TYPE ONLY. ELECTROHYDRAU TYPE ACTUATORS ARE UNACCEPTABLE.

FAN SOUND ATTENUATOR SCHEDULE

SILENCER NO.	FAN SERVED	OVERALL DIMENSIONS WxHxL (FEET–INCHES)	AIR QUANTITY (CFM)	FACE VELOCITY (FPM)	MAX. PRESS. DROP(IN. W.G.)	OCTAVE BAND HERTZ								REMARKS
						63	125	250	500	1K	2K	4K	8K	
						MINIMUM DYNAMIC INSERTION LOSS IN DECIBELS								
SA–1	TVF–1	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–2	TVF–1	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–3	TVF–2	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–4	TVF–2	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–5	TVF–3	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.
SA–6	TVF–3	10'–0" x 12'–0" x 7'–0"	228,000	1,900	0.5	8	13	18	28	40	47	26	18	SEE NOTES 1 AND 2.

NOTES:
1. SIZE AND NUMBER OF MODULES SHALL BE AS REQUIRED TO MEET THE SPECIFIED PERFORMANCE.
2. MINIMUM DYNAMIC INSERTION LOSS VALUES ARE FOR FORWARD FLOW (NOISE AND AIR MOVING IN THE SAME DIRECTION).
3. ATTENUATOR/FAN COMBINED NOISE SHALL BE DEFINED AS THE SPECIFIED FAN NOISE LESS THE SPECIFIED ATTENUATOR DYNAMIC INSERTION LOSS.
4. CONTRACTOR TO ENSURE FAN VENDOR AND ATTENUATOR VENDOR COLLABORATE TO ENSURE THAT THE ATTENUATOR/FAN COMBINED NOISE IS NOT EXCEEDED.
5. CONTRACTOR TO ENSURE FAN VENDOR AND ATTENUATOR VENDOR COLLABORATE DURING FACTORY TESTING. TEST FAN NOISE LEVELS FIRST. ADJUST/MODIFY ATTENUATORS DURING ATTENUATOR TESTS TO ENSURE ATTENUATOR/FAN COMBINED NOISE IS NOT EXCEEDED.

Figure 5.4 – Sample tunnel ventilation fan and sound attenuator schedule.

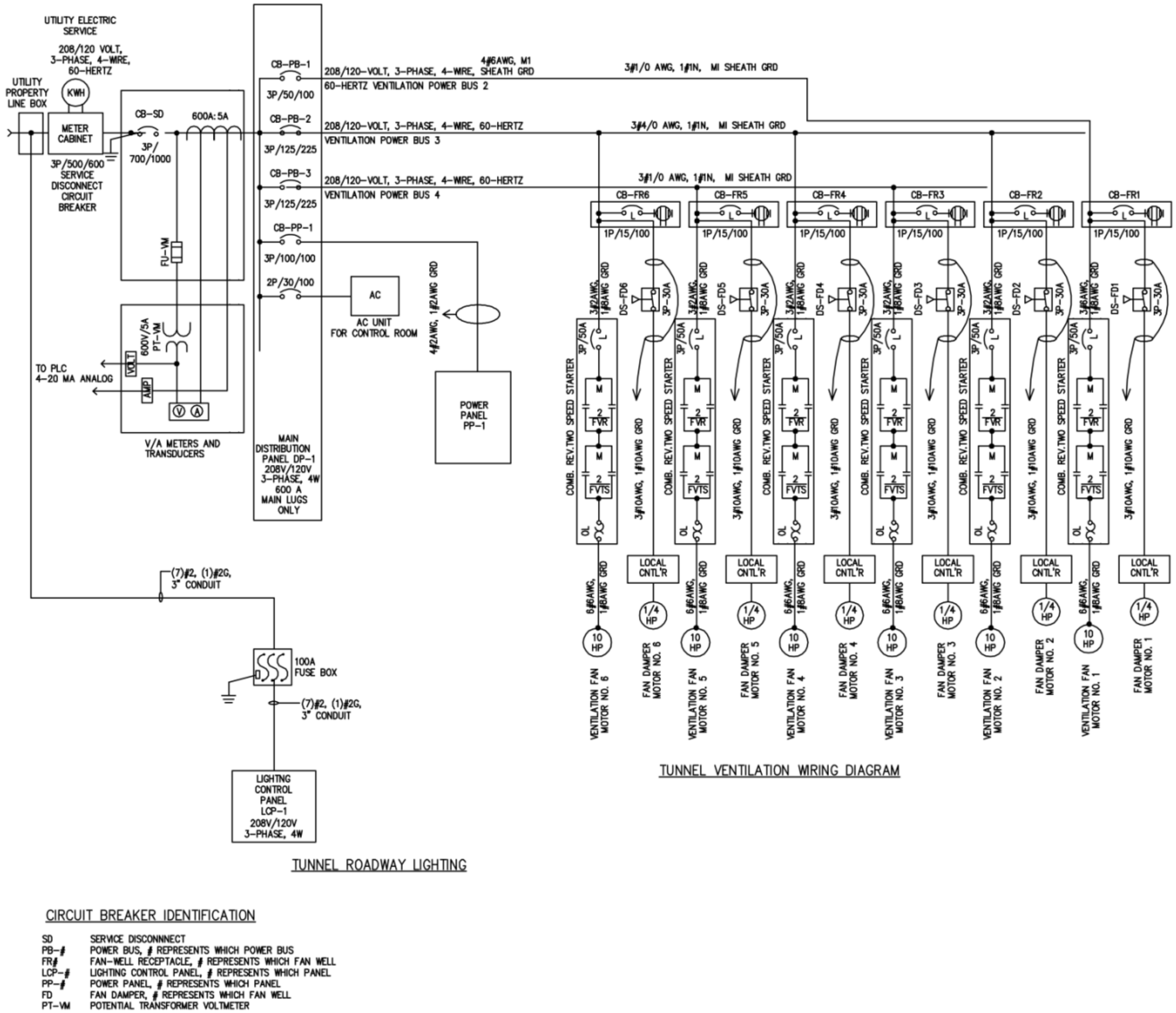

Figure 5.5 – Sample tunnel ventilation and lighting diagram.

5.3.3.2 **Electrical and lighting systems**

The electrical and lighting systems include power distribution system, emergency power distribution system, tunnel lighting and their support fixtures, and emergency lighting and their support fixtures. Figure 5.5 illustrates the type of information that should be understood in the course of evaluating electrical and lighting systems to include various diagrams.

The requirements for electrical and tunnel lighting are usually established by State and local authorities using provisions from building codes, standards, and design guides. The requirements for the electrical and lighting systems should be documented in the file records. If the file records indicate that, for example, the electrical and lighting systems comply with the National Fire Protection Association (NFPA) 70 of the National Electrical Code (2014 Edition) and the American National Standards Institute/Illuminating Engineering Society (ANSI/IES) RP-22 of Tunnel Lighting (2011 Edition), respectively, then these references serve as a basis for establishing the minimum requirements for these systems, as applicable.

Power distribution system – The electrical distribution system consists of the electrical equipment, wiring, conduits, and cables used for distributing electrical energy from the utility supply (service entrance) to the line terminals of utilization equipment. The electrical distribution system may include the following subcomponents: switchgear, unit substations, switchboard, motor control centers, starters, transformers, transfer switches, panel boards, conduits and raceways, and electrical outlets and receptacles.

Emergency power distribution system – This system consists of the electrical equipment, wiring, conduits, and cables used for providing electrical power in case of utility service failure. Equipment included in this system consists of emergency generators and uninterruptible power supply (UPS) systems, transfer switches, and other equipment supplying emergency power. The emergency distribution system may also include the following subcomponents: UPS, batteries, and battery charging equipment. In many tunnels, the UPS limits power supply fluctuations to equipment in the tunnel during normal operations. The mechanical components of the emergency generator are evaluated using techniques for mechanical elements.

Lighting systems – These systems consist of the light fixtures, supports, bulb housings, lenses, light switches, junction boxes, wiring, conduits, cables, sensors, and the controllers. The tunnel lighting system may also include the following subcomponents: photo cell controls and remote ballasts.

Lighting fixtures – Tunnel lighting fixture component supports include anchorage to the supporting member and connecting hardware for the component housing. Fixtures include the physical housing of the lights and their connections to the tunnel structure.

The lights in a tunnel allow the drivers to see objects inside the tunnel and thus serve an important safety function. In the daytime, additional lighting is needed near the entrances to allow time for the driver’s eyes to adjust to the darker conditions within the tunnel while ensuring that the safe stopping-sight-distance is always maintained. Lights are also used during emergencies to illuminate egress routes and provide sufficient light for first responders. When evaluating the effects of several inoperable lights, it is important to consider whether the inoperable lights:

- Are redundant within the lighting system.
- Are only needed for daytime use.
- Are needed for normal tunnel operations.
- Are used for normal operations and during emergency conditions.
- Are connected only to the emergency power distribution system.
- Do not adversely impact the required illumination levels.

Emergency lighting systems and fixtures – These systems consist of the light fixtures, supports, bulb housings, lenses, light switches, junction boxes, wiring, conduits, cables, sensors, and controllers used to provide emergency lighting for the facility. The emergency lighting system may also include the following subcomponents: exit signs, batteries, support space sighting, and remote ballasts.

5.3.3.3 **Fire and life safety systems**

Fire and life safety systems include fire detection systems, fire protection systems, emergency communication systems, and tunnel operation systems. Normally specialists, specialty contractors, or consultants with in-depth knowledge of tunnel operation, emergency response, and technical comprehension of the equipment are needed to evaluate these systems. When evaluating fire and life safety systems, it is important for the tunnel owner to review any significant inspection findings with the fire department that serves the tunnel facility. Figures 5.6 and 5.7 illustrate the type of information that should be understood when evaluating fire and life safety systems. Included in these figures are fire alarm riser and CCTV line diagrams.

The requirements for fire and life safety are usually established by State and local authorities by adopting provisions from building codes, standards, and design guides. The requirements for each tunnel should be documented in the file records or the concept of operations document. If the file records indicate that, for example, the tunnel complies with the National Fire Protection Association (NFPA) 502: Standard for Road Tunnels, Bridges, and Other Limited Access Highways (2014 Edition) or portions of the Municipal fire code, then these references serve as a basis for establishing the minimum requirements for the fire and life safety systems, as applicable.

Fire detection system – The fire detection systems consist of control panels, initiating devices (e.g., heat and smoke detectors, pull-stations), notification appliances (e.g., strobes, horns), wiring, conduits, and cables used to detect a fire in the tunnel. The fire detection system may also include the following subcomponents: sensors, controls, and alarms.

Fire protection systems – The fire protection system consists of fire extinguishers, hose connections, storage tanks, fire hydrants, building sprinklers, pumping systems, piping, circulating pumps, and hose reels. The fire protection system may include the following subcomponents: main fire pump, pressure maintenance/jockey pump, dry pipe valve, valves and tamper switches, storage tanks, tunnel stand pipe, pressure relief and air release valves, backflow prevention, hose stations, hose reels, building sprinklers, water heating systems, fire department connections, and fire hydrants.

5.3.3.4 **Tunnel security systems**

Tunnel operations and security systems consists of the communication equipment (e.g., CCTV cameras, telephones, radios) and various detection equipment. The tunnel operations and security system may also include subcomponents such as: closed-circuit camera system, cell phone antennas, door access, controller, and radio.

The requirements for tunnel security should be established by the tunnel owner. A tunnel specific vulnerability assessment is a valuable tool for determining the security needs of the tunnel. Each tunnel facility typically develops its own set of security requirements based on security protocols and policies established by the tunnel owner.

5.3.3.5 **Emergency communications systems**

Emergency communication systems are integral to both fire and life safety systems and tunnel security systems. The components of the emergency communication system include communication devices (e.g., intercom, radios, cell-phone), receivers, wiring, and exchange devices. The emergency communications system may also include the following subcomponents: signs, controllers, speakers and audio input equipment. Emergency egress signs offer a relatively low-cost way to improve safety, and the recent studies from AASHTO, FHWA, and the World Road Committee (PIARC) should be considered.

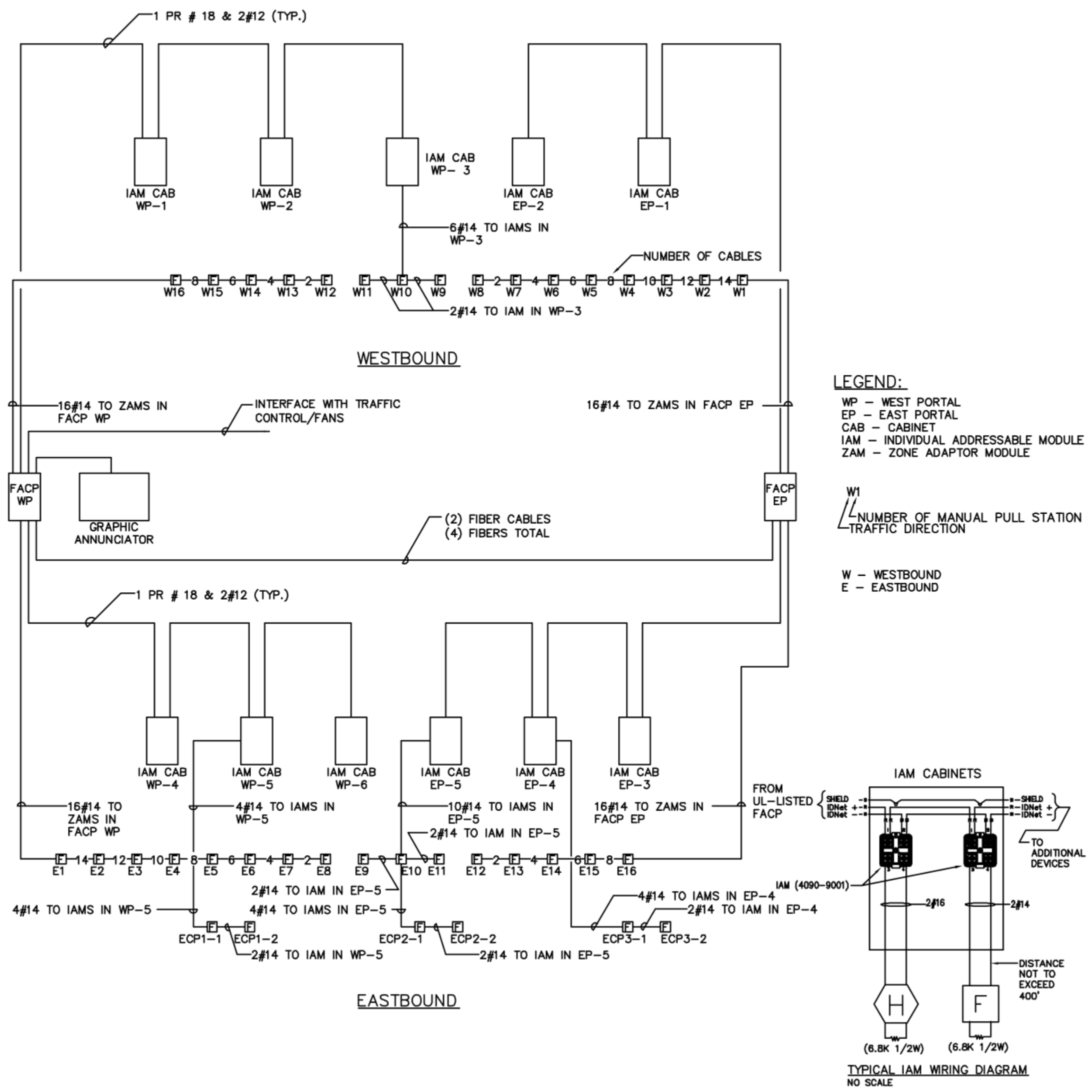

Figure 5.6 – Sample Fire Alarm Riser Diagram.

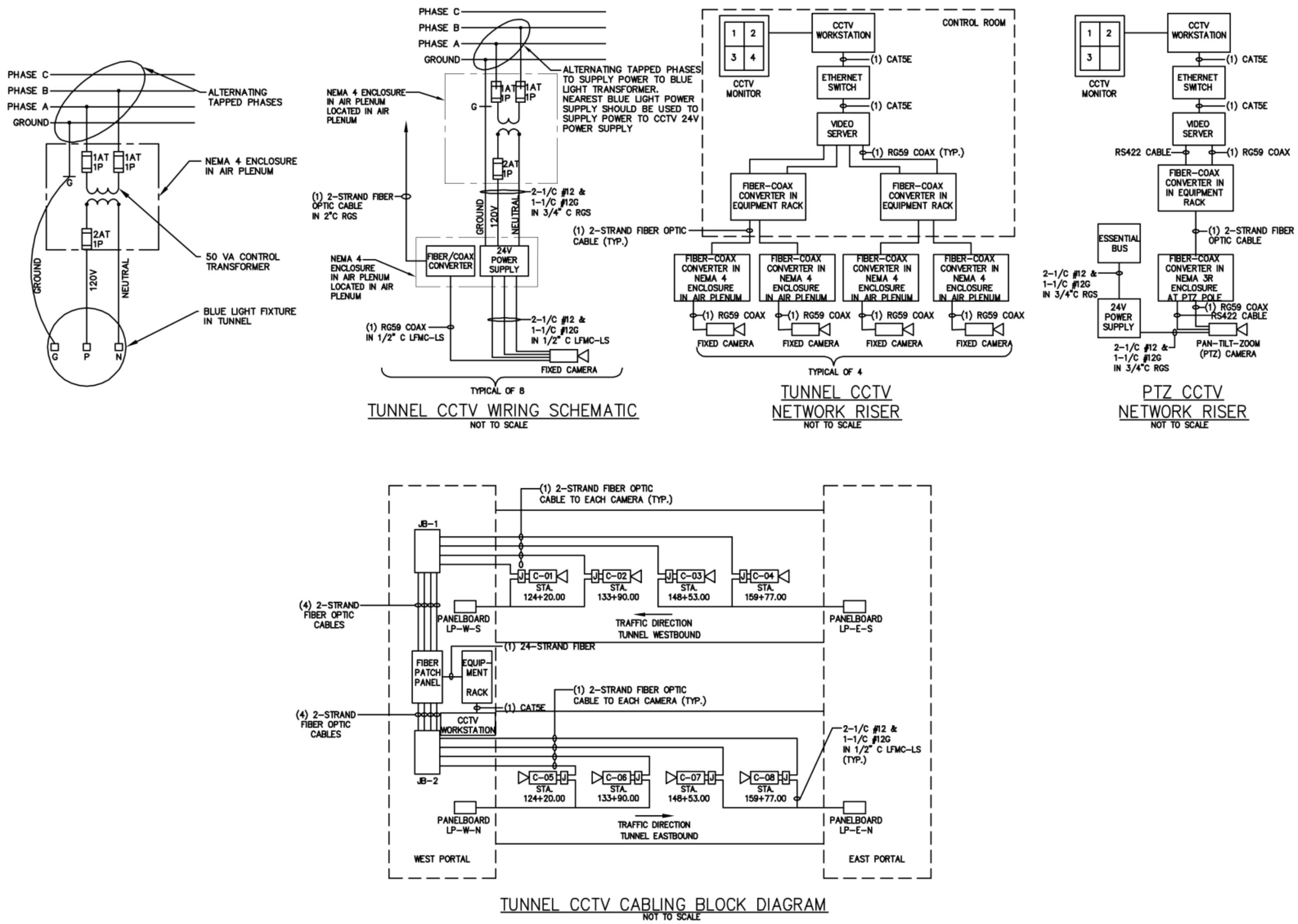

Figure 5.7 – Sample CCTV Line Diagram.

5.3.3.6 Signs and information systems

The sign and information systems include traffic signs, nonemergency egress signs, variable message boards, lane signals, and lane signal fixtures. These systems range from simple signs to complex variable message boards. The requirements for roadway signs are established in the Manual on Uniform Traffic Control Devices.

http://mutcd.fhwa.dot.gov/pdfs/2009r1r2/mutcd2009r1r2edition.pdf

Traffic signs – Traffic signs consist of the traffic sign and supports. Signs for pedestrian egress, variable message signs, and lane signals are not covered under this element.
Egress signs – These elements consist of egress signs and their supports that are not directly related to the emergency lighting system. Proper illumination is necessary to read these signs under emergency conditions.

Variable message boards – Variable message boards consist of the variable message board, supports, associated electrical connections, and computer hardware. These sophisticated devices contain display modules, drivers, power supplies, sensors, fans, dust filters, control cabinets, controllers, input/output circuit boards, modems, and computerized systems.

Lane signals – Lane signals include the lane signal devices, their supports and the control system and some or all of the following subcomponents: signals/fixtures, control station, control cabinets, and conduit.
Lane signal fixtures – Lane signal fixtures include the fixtures, the supports, and the wiring.

5.3.3.7 Protective systems

Protective systems include the protective coating for steel corrosion, concrete weathering, and fire protection.

Steel corrosion protective coating – Steel corrosion protective coating systems include paint, galvanization, or other top coat steel corrosion inhibitor. Additional information on corrosion protection can be found at:

http://www.fhwa.dot.gov/bridge/steel/pubs/if12052/volume19.pdf

Concrete corrosion protective coating – Concrete corrosion protective coating systems include silane/siloxane water proofers, crack sealers such as High Molecular Weight Methacrylate (HMWM), or any top coat barrier that protects concrete from deterioration and reinforcing steel from corrosion.

Fire protective coating – Fire protective coatings include the coating applied to tunnel elements to protect these components from fire.

5.4 Load Rating

Load rating is the determination of the safe vehicular live load carrying capacity. Load ratings are performed using structural plans and information gathered from inspections. The results of the load rating may include load posting to ensure that the roadway has a load capacity equal to or greater than the legal loads or unrestricted routine permit loads for the particular State. A load rating evaluation may be required for issuing hauling permits. A load rating is required for all tunnels that:

- Have a structurally supported roadway system to carry vehicles (not at grade) within the tunnel bore (Figure 5.8 A). The roadway system that carries the vehicles can be treated like a bridge, with a deck, stringers, floor beams, and other members, as applicable.
- Are subjected to live load force effects from a roadway located above the tunnel (Figure 5.8 B). The tunnel liner can be treated like a culvert where earth pressures and live (truck) loads are distributed through fill.

Figure 5.8 – Load rating of tunnels. A) Structurally supported floor; B) Overhead roadway.

The load rating of tunnels shall follow the provisions from the AASHTO Manual for Bridge Evaluation (MBE). In cases where the AASHTO criteria are silent or do not apply, criteria should be agreed upon between the tunnel owner and engineer performing the evaluation, and a record of these decisions shall be documented in the tunnel file. Tunnel ratings are based on information in the tunnel file, including the results from recent field inspections. It is recommended that a qualified geotechnical engineer assist with the evaluation of soil-structure interaction between the tunnel liner, any adjacent elements, and the ground (Figure 5.9).

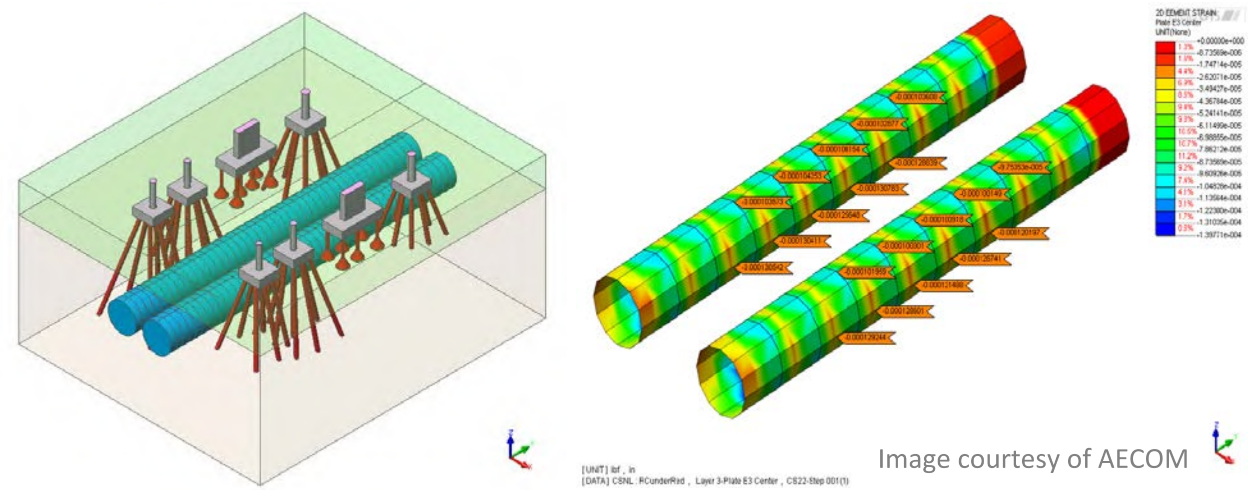

Figure 5.9 – Finite element analysis to mode soil structure interaction.

The load rating may be a simple load rating based on design information, or it may require further engineering analysis. As part of every inspection cycle, tunnel load ratings should be reviewed and updated to reflect any relevant changes in condition or loading noted during the inspection. In the event of a structural or loading condition change at any stage of its service life that may reduce the live load carrying capacity, load ratings should be re-evaluated and updated. Load rating may require a field visit to verify the structural condition.

5.4.1 **Selection of Load Rating Method**

Section 6 of the AASHTO MBE specifies the load rating and posting criteria for highway bridges. Section 8 of the MBE includes the method and criteria for Nondestructive Load Testing for bridge load rating. Load rating and posting for tunnels subject to highway vehicular loads should use the criteria detailed in Sections 6 or 8 of the MBE.

Section 6A of the MBE introduces the Load and Resistance Factor Rating (LRFR) Method, and Section 6B discusses the Allowable Stress Rating (ASR) Method and the Load Factor Rating (LFR) Method. The Federal Highway Administration has issued several policy memoranda regarding the selection of load rating methods. The appropriate load rating method for load rating and posting of tunnels should be selected following FHWA's policy memoranda. Links to these memoranda follow:

Bridge Load Ratings for the National Bridge Inventory, December 22, 1993:

(http://www.fhwa.dot.gov/legsregs/directives/policy/dec22.htm)

This policy memorandum requires that all NHS bridges be rated by the LFR method after 1995.

Bridge Load Ratings for the National Bridge Inventory, October 30, 2006:

(http://www.fhwa.dot.gov/bridge/nbis/103006.cfm)

This policy memorandum further clarifies the selection of load rating methods based on the design method and types of bridges.

The following section will briefly introduce the AASHTO LRFR method only. Refer to Sections 6 and 8 of the MBE for detailed criteria of the LRFR and other load rating methods.

5.4.2 **Load and Resistance Factor Rating (LRFR)**

Tunnel load ratings are performed for various purposes using different live load models and evaluation criteria. Models are used to evaluate the design live load, legal loads, and permit loads. This section describes a systematic approach to tunnel load rating for these load models using the load and resistance factor philosophy; and it aims to address the different uses of load rating results, consistent with the MBE.

The methodology for the load and resistance factor rating of tunnel members is comprised of three distinct procedures:

1) Design load rating
2) Legal load rating
3) Permit load rating

The results of each procedure serve specific purposes and also guide the need for further evaluations to verify tunnel safety or service level. A detailed rating flow chart is included in Appendix A6A in the MBE.

5.4.2.1 **Design Load Rating**

Design load rating is a first-level assessment of tunnel members based on the HL-93 loading and Load and Resistance Factor Design (LRFD) standards, using dimensions and properties of the tunnel in its present as-inspected condition. It is a measure of the performance of existing tunnel members to current LRFD bridge design standards. Under this check, tunnel members are screened for the strength-limit states at the LRFD design level of reliability. Evaluation at a second lower evaluation level of reliability is also an option.

Design load rating can serve as a screening process to identify tunnels that should be load rated for legal loads. Tunnel members that pass the design load check ($RF \geq 1$) at the Inventory level will have satisfactory load rating for all legal loads (and routine permit loads in various States) that fall within the LRFD exclusion limits.

5.4.2.2 Legal Load Rating

This second level rating provides a single safe load capacity (for a given truck configuration) applicable to AASHTO and State legal loads. Live load factors are selected based on the truck traffic conditions at the site. Strength is the primary-limit state for load rating; service-limit states are selectively applied. The results of the load rating for legal loads could be used as a basis for load posting or tunnel member strengthening.

5.4.2.3 Permit Load Rating

Permit load rating checks the safety and serviceability of tunnel members in the review of permit applications for the passage of vehicles above the legally established weight limitations. This is a third-level rating that should be applied only to tunnels having sufficient capacity for AASHTO legal loads. Calibrated load factors by permit type and traffic conditions at the site are specified for checking the load effects induced by the passage of the overweight truck. Guidance is also provided on the serviceability criteria that should be checked when reviewing permit applications.

5.4.2.4 Load Rating Equation

The following general expression should be used in determining the load rating of each component and connection subjected to a single force effect (i.e., axial force, flexure, or shear):

$$RF = \frac{C \pm \gamma_{DC}DC \pm \gamma_{DW}DW \pm \gamma_{EV}EV \pm \gamma_{EH}EH \pm \gamma_{ES}ES \pm \gamma_{P}P}{(\gamma_{LL})(LL+1M) \pm \gamma_{LS}LS}$$

In which, for the Strength Limit States:

$$C = \varphi_c \varphi_s \varphi R_n$$

Where the following lower limit shall apply:

$$\varphi_c \varphi_s \geq 0.85$$

And, for the Service Limit States:

$$C = f_R$$

where:

RF = Rating factor

C = Capacity

f_R = Allowable stress specified in the LRFD code

R_n = Nominal member resistance (as inspected)

DC = Dead load effect due to structural components and attachments

DW = Dead load effect due to wearing surface and utilities

EV = Vertical earth pressure

EH = Horizontal earth pressure

ES = Uniform earth surcharge

LS = Live load surcharge

P = Permanent loads other than dead loads

LL = Live load effect

IM = Dynamic load allowance

γ_{DC} = LRFD load factor for structural components and attachments

γ_{DW} = LRFD load factor for wearing surfaces and utilities

γ_{EV} = LRFD load factor for vertical earth pressure

γ_{EH} = LRFD load factor for horizontal earth pressure

γ_{ES} = LRFD load factor for uniform earth surcharge

γ_{LS} = LRFD load factor for live load surcharge

γ_{P} = LRFD load factor for permanent loads other than dead loads = 1.0

γ_{LL} = Evaluation live load factor

φ_c = Condition factor

φ_s = System factor

φ = LRFD resistance factor

5.4.2.5 Limit States

The load rating should be carried out at each applicable limit state and load effect, with the lowest value determining the controlling rating factor. Limit states and load factors for load rating should be selected from the MBE.

Components subjected to combined load effects should be load rated considering the interaction of load effects (i.e., axial-bending interaction or shear-bending interaction).

5.4.2.6 Resistance Factors

Use of Condition Factors as presented below may be considered optional based on an agency's load-rating practice.

The condition factor provides a reduction to account for the increased uncertainty in the resistance of deteriorated members and the likely increased future deterioration of these members during the period between inspection cycles.

System factors are multipliers applied to the nominal resistance to reflect the level of redundancy of the complete superstructure system. Tunnel components that are less redundant will have their factored member capacities reduced and, accordingly, will have lower ratings.

The system factors in Table 6A.4.2.4-1 of the MBE are more conservative than the LRFD design values and may be used at the evaluator's discretion until they are modified in the AASHTO LRFD Bridge Design Specifications.

5.4.3 Loads and Load Distribution

Simplified live load distribution equations specified in AASHTO LRFD Design Specifications Article 4.6.2 should be used in load rating analysis as appropriate.

5.4.4 Refined Structural Analysis

Tunnel members may be analyzed by refined methods of analysis as described in AASHTO LRFD Design Specifications Article 4.6.3 when they exhibit insufficient load capacity when analyzed by approximate methods. Tunnels or loading conditions for which accurate live load distribution formulas are not readily available can also use these methods.

5.4.5 Load Rating Based on Engineering Judgment

In instances where necessary details, such as reinforcement in the tunnel, are not available from plans or field measurements, a physical inspection by a qualified inspector and evaluation by a qualified engineer may be sufficient to establish an approximate load rating based on rational criteria.

Stringer-supported concrete deck slabs and metal decks that are carrying normal traffic satisfactorily need not be routinely evaluated for load capacity. The decks should be inspected regularly to verify satisfactory performance. The inspection of metal decks should emphasize identifying the onset of fatigue cracks.

5.4.6 Documentation of Load Rating

The load rating should be fully documented including all background information such as field inspection reports, material, and load test data, all supporting computations and a clear statement of all assumptions used in calculating the load rating. If a computer model was used, the input data file should be retained for future use.

5.4.7 Quality Assurance and Quality Control

Quality control procedures are intended to maintain the quality of the bridge load ratings and are usually performed continuously within the load rating teams or unit. When a consultant performs load ratings, the consultant must have quality control procedures in place to ensure the accuracy and completeness of the load ratings. All load rating calculations must be checked by a qualified engineer other than the load rating engineer. Upon completion, the initials of the reviewer are to be placed on every sheet of the calculations.

Quality assurance procedures are used to verify the adequacy of the quality control procedures to meet or exceed the standards established by the agency or the consultant performing the load ratings. Quality assurance procedures are usually performed independently of the load rating teams on a sample of their work. Guidance on quality measures for load rating may be found in MBE Article 1.4.

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