Technical Memorandum

Heroes Tunnel Project

Heroes Tunnel Project Ventilation Study

State Project No. 167-108

October 2019

Prepared for:

Connecticut Department of Transportation

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Acronym List

A .... Ampere
AHJ .... Authority Having Jurisdiction
ASET .... Available Safe Egress Time
ATS .... Automatic Transfer Switch
BFRL .... Building and Fire Research Laboratory
C .... Celsius
CCTV .... Closed Caption Television
cd .... candela
CFD .... Computational Fluid Dynamics
cfm .... cubic feet per minute
CO .... Carbon Monoxide
CPU .... Central Processing Unit
CTDOT .... Connecticut Department of Transportation
CTI .... Confirmed Temperature Initiation
DMS .... Dynamic Message Signs
DNS .... Direct Numerical Simulation
DPW .... Department of Public Works
e.g. .... For Example
F .... Fahrenheit
FDC .... Fire Department Connections
FDS .... Fire Dynamics Simulator
FHWA .... Federal Highway Administration
ft .... foot/feet
FVM .... Finite Volume Method
g .... Gram
HRR .... Heat Release Rate
Hz .... Hertz
IBC .... International Building Code
IES .... Illuminating Engineering Society
IESNA .... Illuminating Engineering Society of North America
IFC .... International Fire Code
in .... Inch
kg .... kilogram
kVA .... kilo-Volt-Amperes
kW .... kilowatt
LES .... Large Eddy Simulation
LPS .... Low-Pressure Sodium
m .... meter
MCC .... Motor Control Center
mcd .... millicandela
mg .... milligram
MUTCD .... Manual on Uniform Traffic Control Devices

MW .... Megawatts
NCHRP .... National Cooperative Highway Research Program
NEC .... National Electric Code
NEMA .... National Electrical Manufacturers Association
NFPA .... National Fire Protection Association
NIST .... National Institute of Standards and Technology
ppm .... Parts per Million
RSET .... Required Safe Egress Time
s .... second
SFPE .... Society of Fire Protection Engineers
SI .... International System (units)
TOMIE .... Tunnel Operations, Maintenance, Inspection, and Evaluation Manual
UPS .... Uninterruptible Power Supplies
US .... United States (units)
W .... Watt

Section 1

Executive Summary

The Heroes Tunnel carries the Wilbur Cross Parkway (Route 15) through the West Rock Ridge in the City of New Haven and the Towns of Woodbridge and Hamden. The Connecticut Department of Transportation (CTDOT) conducts routine tunnel inspections on a biennial basis with a special inspection of the tunnel liner on the off years. The most recent inspection reports have categorized the Ventilation System, Fans, Electrical Distribution System, Fire Detection System, Fire Protection System, Emergency Communications System, and Traffic Sign elements to be in Condition State 4. As described in FHWA's Specifications for the National Tunnel Inventory, included in Appendix H, a Condition State 4 warrants evaluation to determine the effect on serviceability of the specific element and tunnel overall.

As a result, CTDOT tasked CDM Smith with conducting this evaluation and performing an analysis to determine what is needed to address the Ventilation System, Fans, Electrical Distribution System, Fire Detection System, Fire Protection System, Emergency Communications System, and Traffic Sign deficiencies. The National Fire Protection Association (NFPA) 502 Standard for Road Tunnels, Bridges and Other Limited Access Highways, 2017 specifications were used as the standards for the evaluation and analysis of ventilation and electrical systems. These would be the standards used when designing a new tunnel or major renovations to an existing tunnel.

The NFPA 502 is referenced throughout the AASHTO LRFD Road Tunnel Design and Construction Guide Specifications (2017); most notably under Section 2.8.3, which states, "the Tunnel Ventilation System shall be designed to maintain environmental conditions within the tunnel and shall also meet the requirements of NFPA 502 for fire and smoke control." This evaluation and analysis also adheres to the requirements specified under Sections 2.8.5 Lighting, 2.8.6 Electrical Systems, and 2.8.8 Fire Protection from the LRFD Tunnel Guide Specifications.

The NFPA 502 states, "The engineering analysis should be used to guide the decision process by the stakeholders and the Authority Having Jurisdiction (AHJ) for implementation of specific fire protection and life safety requirements." This evaluation and analysis has not selected the treatments or other improvements and procedures to satisfy the fire protection and life safety concerns but provided recommendations and alternatives to help guide the decision. The selection of the proposed treatments, improvements, and procedures will be included as part of the Preliminary Design phase.

The NFPA 502 requirements for this facility type along with the existing condition of the elements of the Heroes Tunnel are presented in Section 3.0. The criteria, methods and evaluations performed in the study are presented in Section 4.0, and the results of those analyses in Section 5.0. The upgrades to the Heroes Tunnel necessary to meet current NFPA 502 code requirements are presented in Section 6.0; a summary is provided below:

Ventilation System. Engineering analysis indicates that a pro-active system is required. A proposed system would consist of:

- Six (6) unidirectional longitudinal 50,000 cfm jet fans per barrel to be automated, zone controlled and activated to respond to a fire incident in one of three (3) zones in the tunnel or due to CO levels exceeding the allowable threshold.
- Two (2) 82,500 cfm exhaust fans at the top of the existing central shaft ventilation ducts to supplement the jet fans for a fire incident in the middle zone of a tunnel barrel
- Reconstruction of the inlet ducts and vents at tunnel level, repair of the ventilation shafts, mounting the fans, and rehabilitation of the ventilation building at the top of West Rock Ridge
- Electric control communication system for the automated operation of the ventilation system, including fire detection and carbon monoxide detectors

Fire Detection and Fire Protection Systems. NFPA requires a dry fire protection standpipe system with connections to fire department water systems, a fire detection system, portable fire extinguishers, and an emergency two-way radio communication system.

- Fire protection standpipes running the full length of each tunnel barrel with connections spaced at 150 feet and end connections to local fire department hydrants
- Extension of local fire department water systems and new fire hydrants at each tunnel portal
- New portable fire extinguishers in NFPA 10 approved cabinets
- Fire alarm system

Traffic Control. A means of stopping traffic at approach portals before entering the tunnel is required. Traffic control will also assist in egress requirements.

- Two truss sign support structures and foundations with lane use control signs, one along Route 15 southbound at the northern portal and one at Route 15 northbound at the southern portal
- Two portal mounted support structures with lane use control signs, one along Route 15 southbound at the northern portal and one at Route 15 northbound at the southern portal

Emergency Egress. Emergency egress signage and lighting is required. As per NFPA 502 the new traffic control system that stops traffic from entering the tunnel during an incident allows the tunnel travel way to be used as an egress pathway. To meet emergency egress requirements the existing abandoned control room at the center of the tunnel will be reconstructed to function as an emergency egress cross passage between the two tunnel barrels.

- Emergency egress signage
- Reconstruction of control room into emergency egress cross passage

Electrical Systems and Lighting. Complete replacement of the entire electrical system is needed based on new loading and the poor condition of the existing electrical systems. The replacement of the existing tunnel lighting system with center mounted LED fixtures that adapt to the tunnel lighting requirements of both daytime and nighttime illumination is proposed.

- New LED Tunnel lighting – 260 fixtures with PLC lighting control system and light sensors
- New Power Distribution System housed in a prefabricated climate-controlled building
- New emergency generator set on concrete pad foundation
- Electrical lighting and power for new ventilation system, egress cross passage, and ventilation exhaust building

Structural Improvements to the Existing Tunnel. Mounting the new ventilation system, tunnel lighting, and standpipes to the existing tunnel ceiling and walls as well as the rehabilitation of the ventilation exhaust building at the top of the ridge, and the reconstruction of the existing control room into an egress cross passageway will be required. The leakage and cracking in the existing ventilation shafts will also be addressed.

Estimated Construction Cost = $20,150,000 (2021 construction season) *
Estimated Project Cost = $25,020,000 (includes design and incidentals) *

*see Appendix G for Opinion of Probable Cost

Section 2

Introduction

The Heroes Tunnel carries the Wilbur Cross Parkway (Route 15) through the West Rock Ridge in the City of New Haven and the Towns of Woodbridge and Hamden. The Heroes Tunnel is a 1,200-foot long tunnel, which passes through West Rock Ridge in New Haven and Woodbridge, as illustrated on Figure 2-1. The existing tunnel was constructed between spring 1948 and fall 1949 and consists of two 28-foot wide by 19-foot high barrels with horseshoe cross-sections. The northbound and southbound barrels of the tunnel consist of two 11-foot wide travel lanes with 6-inch shoulders and a 2-foot 6-inch wide raised maintenance walk on each side. The centerlines of the barrels are approximately 63 feet apart. It is the only tunnel to pass beneath a natural land feature in the State of Connecticut and is eligible for listing on both the National and State Registers of Historic Places.

The Connecticut Department of Transportation initiated this Ventilation Study to identify the fire and life safety deficiencies in the existing tunnel. The 2017 In-Depth Inspection Report on Tunnel No. 00773 categorized the following element numbers into Condition State 4 (CS4):

Table 2-1 Heroes Tunnel (Tunnel No. 00773) Condition State 4 Elements

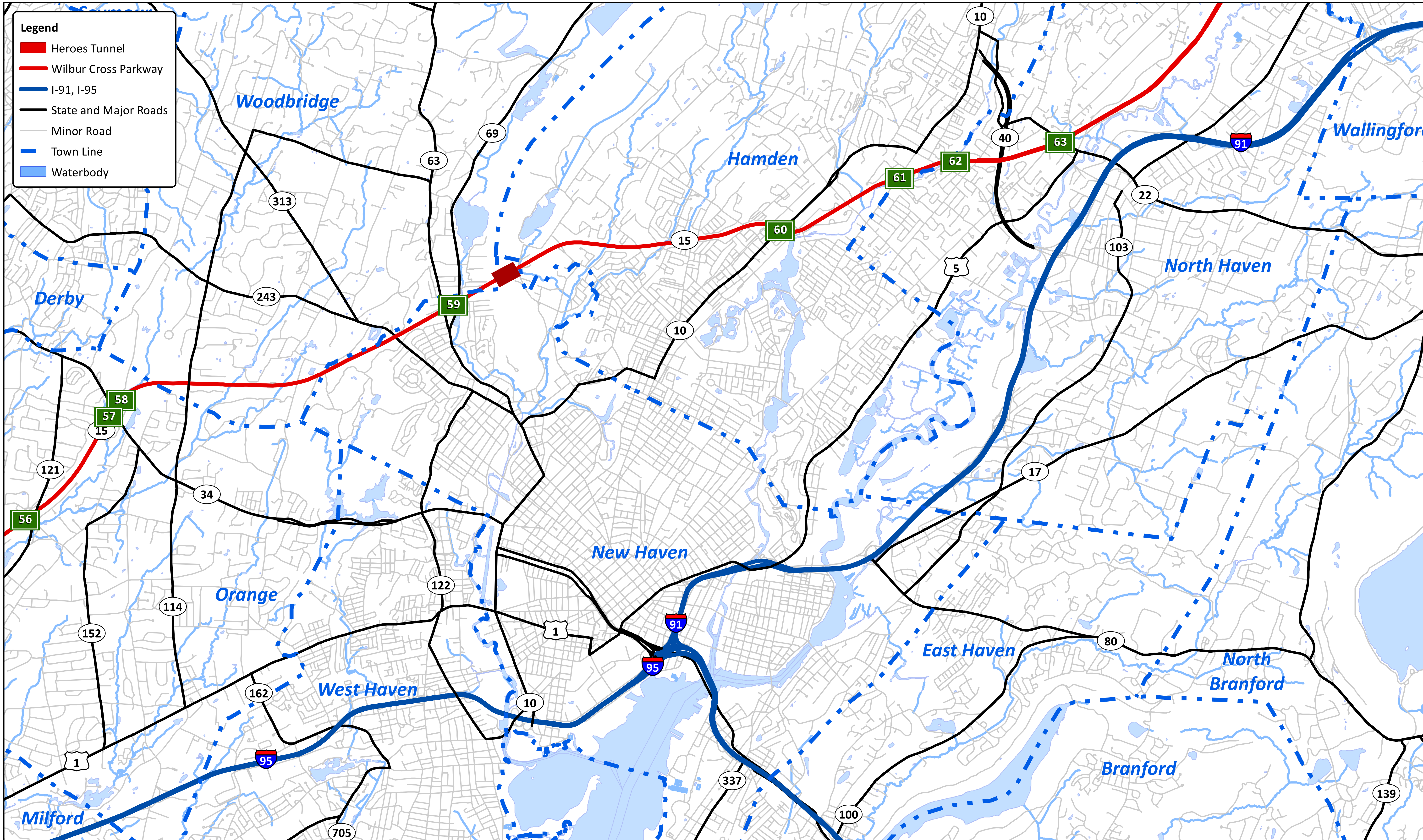
Element	Percentage in CS4
10200 Ventilation System	100%
10201 Fans	100%
10500 Electrical Distribution System	100%
10650 Fire Detection System	100%
10700 Fire Protection System	100%
10750 Emergency Communications	100%
10850 Traffic Sign	100%

Elements that fall under Condition State 4 warrant evaluation to determine the effect on serviceability of the element or tunnel. The Condition State definitions for each of the noted elements, as per FHWA's Specifications for the National Tunnel Inventory, is provided in Appendix H.

This study evaluated and analyzed all noted elements in Condition State 4 and their code requirements as per the AASHTO LRFD Tunnel Guide Specifications and NFPA 502. The study notes deficiencies of these elements, the required upgrades to bring these elements to code compliance, and the probable cost associated with these upgrades.

These upgrades were determined through an engineering evaluation and analysis of the fire protection, fire detection, and life safety requirements for the existing tunnel. A review and evaluation of the existing electrical systems, emergency and egress signs, lighting, and traffic control is also presented.

This study provides recommendations and alternatives to help guide the selection of the proposed treatments, improvements, and procedures by the stakeholders and AHJ. The AHJ for the Heroes Tunnel fire and life safety is the CT State Fire Marshall.



Data Sources:
- Connecticut Department of Energy and Environmental Protection
- South Central Regional Council of Governments

Date: April 2019

Regional Map

0 2,000 4,000 6,000 8,000
Feet

Heroes Tunnel Project

FIGURE 2-1

Section 3

System Requirements and Existing Conditions

3.1 Introduction of Standards, Codes, and Evaluation Criteria

This document has been prepared to summarize and document the fire and life safety aspects of a performance-based fire protection design approach as outlined in the Society of Fire Protection Engineers (SFPE) *Guide to Performance-Based Fire Protection* to meet the intent of the NFPA 502. The 2015 Edition of International Code Council Codes are the adopted referenced codes and standards for this project.

The overall goal of this study is to model the tunnel, shaft structures and all of its components in the way in which it is designed to function. The results of the model will then be analyzed to see if the space meets the minimum visibility limits set forth by SFPE Fire Protection Engineering Handbook. The intent of this report is to document the tenability conditions throughout each fire scenario.

Furthermore, this document describes the approach and conclusion of the fire and egress modeling analysis performed to meet the prescriptive intent of the applicable codes and standards. The modeling was based around the following code requirements at a minimum, except where noted otherwise in this report:

- NFPA 13, *Standard for the Installation of Sprinkler Systems* 2013 Edition
- NFPA 14, *Standard for Installation of Standpipe and Hose Systems* 2013 Edition
- NFPA 24, *Standard for the Installation of Private Fire Service Mains and Their Appurtenances* 2013 Edition
- NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems* 2014 Edition
- NFPA 72, *National Fire Alarm Code* 2013 Edition
- NFPA 291, *Recommended Practice for Fire Flow Testing and Marking of Hydrants* 2013 Edition
- NFPA 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways* 2017 Edition
- AASHTO LRFD Road Tunnel Design and Construction Guide Specifications 2017 Edition
- NCHRP 216 Emergency Exit Signs and Marking Systems for Highway Tunnels
- NCHRP 836 Guidelines for Emergency Ventilation Smoke Control in Roadway Tunnels
- 2018 Connecticut State Building Code

- 2015 International Building Code (IBC)
- 2015 International Fire Code (IFC)
- U.S. Department of Transportation Technical Manual for Design and Construction of Road Tunnels – Civil Elements

The Performance-Based fire protection design will follow the design guidance described in:

- SFPE *Engineering Guide to Performance-Based Fire Protection* 2nd Edition
- SFPE *Fire Protection Engineering Handbook* 5th Edition

The State of Connecticut utilizes the 2018 Connecticut State Building Code, which references the 2015 International Building code. Although the Connecticut State Building code does not directly reference NFPA 502 *Standard for Road Tunnels, Bridges, and Other Limited Access Highways* (2017 Edition), it is referenced in the U.S. Department of Transportation Technical Manual for Design and Construction of Road Tunnels – Civil Elements. The U.S. Department of Transportation Technical Manual for Design and Construction of Road Tunnels – Civil Elements, requires the most current edition of NFPA 502 to be used. NFPA 502 *Standard for Road Tunnels, Bridges, and Other Limited Access Highways* is the main focus of the code analysis, as it establishes the fire protection requirements for Road Tunnels, Bridges, and Other Limited Access Highways.

3.2 Fire Detection

3.2.1 Standards, Codes, and Evaluation Criteria

According to NFPA 502, Heroes Tunnel is considered to be a Category C tunnel, due to the length of the tunnel exceeding 1000 feet. As a Category C tunnel, at least one manual means of identifying and locating a fire is required. A manual means of identifying and locating a fire consists of manual fire alarm boxes mounted in NEMA Enclosure Type 4 (IP 65) or equivalent boxes at intervals of not more than 300 feet and at all cross-passages and means of egress from the tunnel. In addition, since no 24-hour supervision is provided throughout the tunnel, an automatic fire detection system is required in accordance with NFPA 502, section 7.4.7. Section 7.4.7 of NFPA 502 requires an automatic fire detection system installed in accordance with NFPA 72.

Signals for the purpose of evacuation and relocation of occupants is not required, but automatic fire detection capable of identifying the location of a fire within 50 feet is required. A fire alarm control panel shall also be installed, inspected, and maintained in accordance with NFPA 72. Currently, no fire alarm system is installed.

Additionally, two-way radio communication systems shall be installed in new and existing tunnel, where required by the AHJ. This two-radio communication will need to be discussed with the AHJ to determine the best solution for two-way radio communication and what this requirement entails.

3.2.2 Existing Conditions

Presently there is no fire detector system functioning within the tunnel. The original design did have a fire alarm system activated at the removal of fire extinguishers within the tunnel.

3.3 Means of Egress

3.3.1 Standards, Codes, and Evaluation Criteria

Egress from the tunnel shall have a spacing between exits not exceeding 1000 feet, according to NFPA 502.

3.3.2 Existing Conditions

Currently the tunnel does not meet emergency egress requirements since the central control room gates are locked and no fire door is installed this cannot be an egress point. Tunnel portals are 1200 feet apart exceeding maximum egress pathway limits and the roadway cannot be egress parkway given no existing traffic control. Also existing 28 inch curbs do not meet minimum egress pathway widely at 43 inches.

3.4 Fire Protection

3.4.1 Portable Fire Extinguishers

3.4.1.1 Standards, Codes, and Evaluation Criteria

In addition to the fire alarm requirement, NFPA 502 requires portable fire extinguisher to be placed along the roadway in approved wall cabinets at intervals of no more than 300 feet. A minimum of a 2-A:20-B:C fire extinguisher spaced every 300 feet in an approved wall cabinet is required. The fire extinguisher mounting and cabinet must meet the requirements of NFPA 10. In order to ensure occupants have enough clearance to egress on the egress path, fire extinguisher cabinets shall be recessed into the tunnel walls.

3.4.1.2 Existing Conditions

Presently there is no portable fire extinguishers in the tunnel. The original construction provided insets in the tunnel liner that held portable fire extinguishers speed at 150 feet.

3.4.2 Water-Based Fire-Fighting System

3.4.2.1 Standards, Codes, and Evaluation Criteria

A fixed water-based fire-fighting system shall be mandatory in category C and Category D tunnels, according to NFPA 502. The goal of the water-based fire-fighting system shall be to slow, stop, or reverse the rate of fire growth or otherwise mitigate the impact of the fire to improve tenability conditions within the tunnel and enhance in the ability of first responders to aid in evacuation and/or protect the major structural elements of the tunnel.

3.4.2.2 Existing Conditions

There is presently no fixed water-based fire lighting system installed in the tunnel barrels.

3.4.3 Fire Standpipe

3.4.3.1 Standards, Codes, and Evaluation Criteria

According to NFPA 502, if the tunnel length is 300 feet or greater a standpipe system shall be installed in accordance with the requirements of Chapter 10 of NFPA 502. The standpipe system shall be installed as a Class I system. Since it is subject to freezing, the standpipe shall be a dry standpipe system. The system shall be designed for a water supply capable of supplying the system demand for a minimum of 1 hour. Each independent standpipe system shall have a minimum of two fire department connections that are remotely located from each other.

Standpipe systems shall be installed in accordance with NFPA 14 and inspected and maintained in accordance with NFPA 25. NFPA 502, chapter 10, allows a maximum travel distance of 150 feet between hose connections. The most remote standpipe shall have a flow of 500 GPM through the two most remote 2 ½ inch outlets, per NFPA 14. This results in a total of 5 standpipe connections per tunnel barrel. Figure 3-1 illustrates the proposed standpipes within the tunnel.

In addition to standpipes, fire hydrants will need to be added near the tunnels. According to NFPA 14, section 6.4.5.4, fire department connections shall be located not more than 100 feet from the nearest fire hydrant. Currently, there are no fire hydrants within 100 feet of the tunnel portals. It is proposed to place two new hydrants on either side of the tunnels to allow for this code requirement to be met. Figure 3-2 illustrates the existing and proposed fire hydrant locations.

3.4.3.2 Existing Conditions

There presently is no fire standpipe system installed within the tunnel.

3.4.4 Emergency Ventilation System

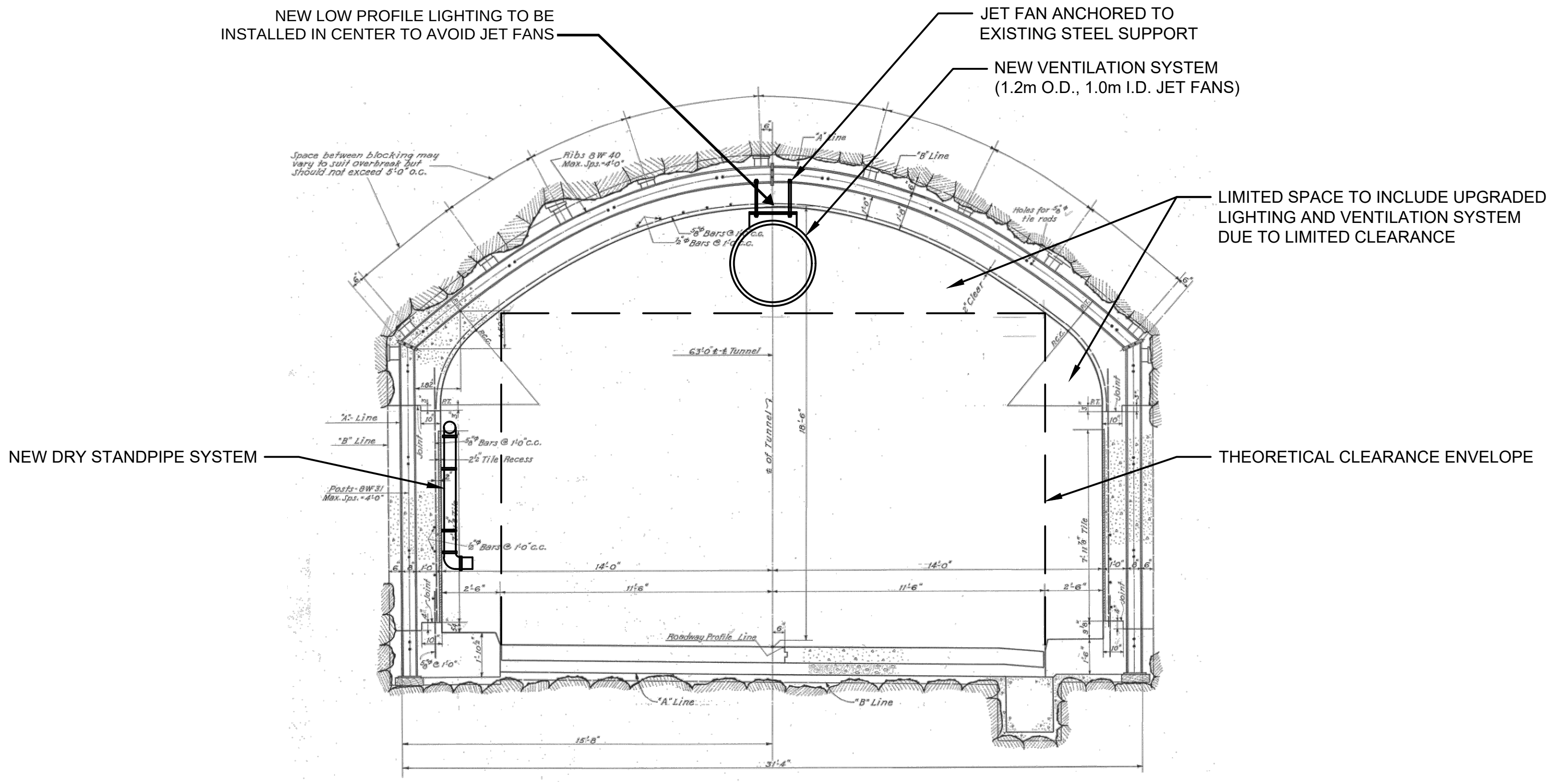
3.4.4.1 Standards, Codes, and Evaluation Criteria

Emergency ventilation shall not be required in tunnels less than 3,280 feet in length, where it can be shown by engineering analysis that the level of safety provided by a mechanical ventilation system can be equaled or exceeded by enhancing the means of egress, the use of natural ventilation, or the use of smoke storage, and shall be permitted only where approved by the authority having jurisdiction.

The design of an emergency ventilation system shall be based on fire scenarios having defined heat release rate, smoke release rates, and carbon monoxide (CO) release rates. The design fires shall be sized based on a heat release rate provided by vehicle(s) and shall consider the types of vehicles that are expected to use the tunnel.

3.4.4.2 Existing Conditions

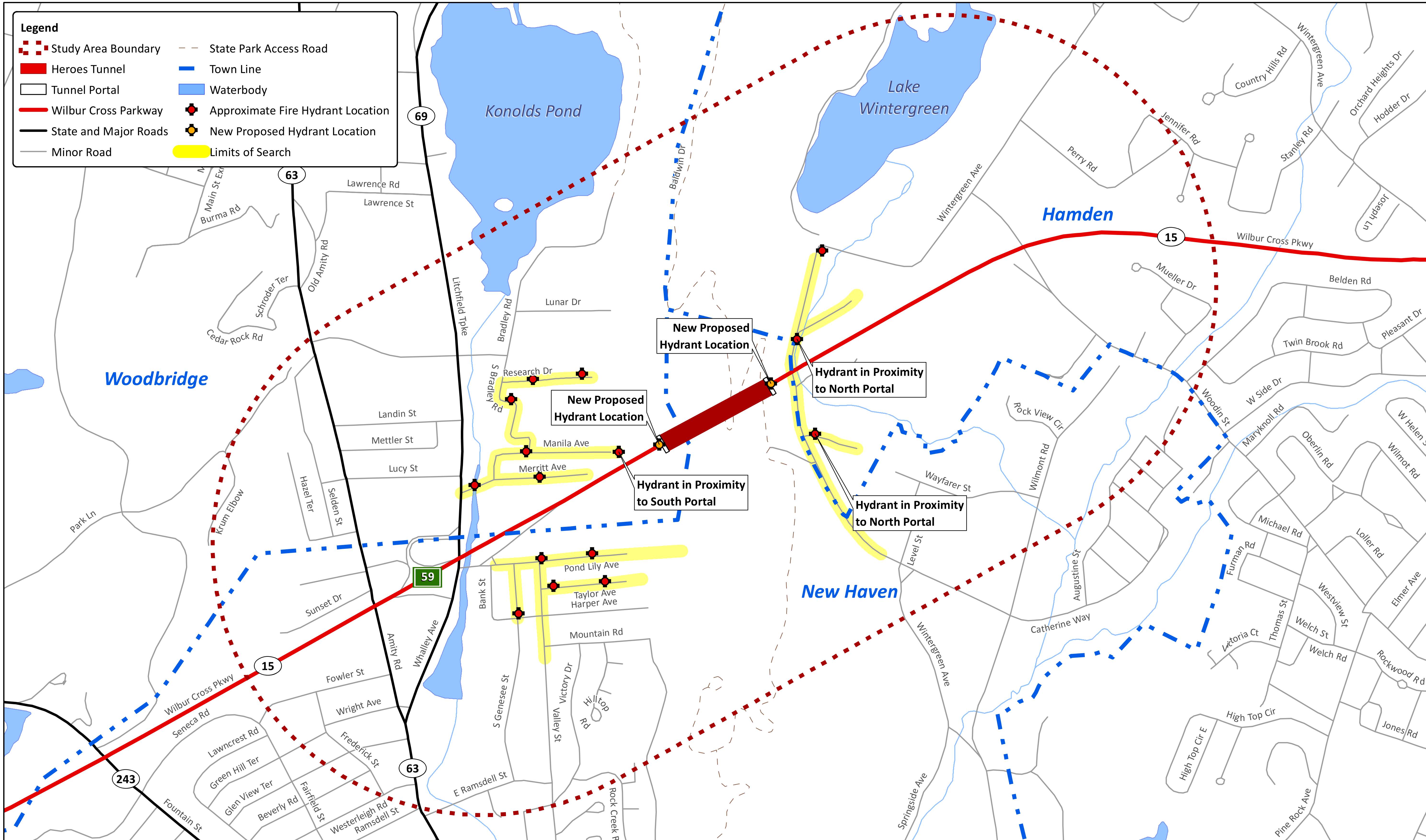
Heroes Tunnel was originally constructed with ventilation shafts. Since then the fans for the ventilation shaft have been removed. The original ventilation system consisted of (4) 82.500 cubic feet per minute (cfm) fans. Two fans were used to serve the north tunnel and two were used to serve the south tunnel. The fans have since been removed and currently no ventilation system is in place. In 2009, CDM Smith conducted an inspection of the ventilation shaft and it was found that the ventilation structure appears to be in fair to good condition. Some leaking construction, cracks, spalls and scaling was found.



TYPICAL TUNNEL BARREL CROSS SECTION

Figure No. 3-1

TYPICAL TUNNEL BARREL CROSS SECTION



Data Sources:

- Connecticut Department of Energy and Environmental Protection
- South Central Regional Council of Governments

Date: June 2019

Hydrant Locations within Proximity of Heroes Tunnel

0 300 600 900 1,200
Feet

Heroes Tunnel Project

FIGURE 3-2

3.5 Fire Protection of Structural Elements

3.5.1 Standards, Codes, and Evaluation Criteria

NFPA 502, Chapter 7, discusses the requirements for fire protection of roadway tunnels. Based on Section 7.2, Heroes Tunnel is classified as a Category C type tunnel and shall satisfy all NFPA 502 provisions. Section 7.3 specifically addresses protection of structural elements for road tunnels. According to NFPA 502, acceptable means shall be included within the design of the tunnel to protect the primary structural concrete and steel elements to achieve support for fire fighter accessibility, to mitigate structural damage and prevent collapse, and minimize economic impact. Sections 7.3.2 through 7.3.4 clearly articulate the requirements for protection of structural elements.

Additionally, the structure elements shall be protected to achieve a temperature of cast in-situ concrete surface to not exceed 716°F, steel or cast iron within the concrete to not exceed 200°C 572°F, and steel reinforcement to withstand 482°F.

3.5.2 Existing Conditions

The existing structural system (tunnel liner) that provides permanent support to the rock mass is reinforced concrete, with #4 and #5 reinforcing bars at typical spacing, and with 2-in clear cover to reinforcement. During construction, where the rock mass had to be supported prior to the tunnel liner being installed, steel sections, typically W8X31 with blocking, were utilized.

Without physical testing of the concrete liner to ascertain material properties and asses material condition and without performing computational fluid dynamic (CFD) modelling and numerical structural analysis that accounts for material property changes, it is difficult to quantify performance of the existing structural elements subjected to elevated temperatures to meet current NFPA 502 requirements.

At the time of construction of the Heroes Tunnel, standards such as those currently established by the NFPA for road tunnels did not exist. Therefore, it is likely that the tunnel structural elements were not designed to meet any requirements to prevent collapse due to fire and their state of deterioration could further limit these elements capability to withstand these temperature exposures.

3.6 Traffic Control

3.6.1 Standards, Codes, and Evaluation Criteria

In the event of a fire incident, traffic control requirements for road tunnels are governed by National Fire Protection Association (NFPA) 502, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways: Section 7 Road Tunnels.* Supplemental guidance on emergency signage and marking systems within tunnels are provided within the National Cooperative Highway Research Program (NCHRP) Web-Only Document 216, *Proposed Guidelines for Emergency Exit Signs and Marking Systems for Highway Tunnels.* Traffic control along Route 15 in advance of Heroes Tunnel is governed by the 2009 Manual on Uniform Traffic Control Devices (MUTCD) along with Connecticut Department of Transportation (CTDOT) standards.

3.6.1.1 Tunnel Traffic Control

According to NFPA 502 Section 7.6, all road tunnels must provide a means to stop approaching traffic in response to emergency conditions. Furthermore, tunnels longer than 800 feet (applicable to Heroes Tunnel) must provide means to stop traffic from entering the tunnel, control traffic already within the tunnel, and also clear traffic downstream of the site of the emergency.

Specifically, the following extracted requirements are defined under Section 7.6.2:

1. Direct approaches to the tunnel shall be closed following activation of a fire alarm within the tunnel. Approaches shall be closed in such a manner that responding emergency vehicles are not impeded in transit to the fire site.

2. Traffic within the tunnel approaching (upstream of) the fire site shall be stopped prior to the fire site until it is safe to proceed as determined by the incident commander.

3. Means shall be provided downstream of an incident site to expedite the flow of vehicles from the tunnel. If it is not possible to provide such means under all traffic conditions, then the tunnel shall be protected by a fixed water-based fire-fighting system or other suitable means to establish a tenable environment to permit safe evacuation and emergency services access.

4. Operation shall be returned to normal as determined by the incident commander.

Section 7.16 Emergency Exits requires that exits for protection of tunnel occupants not exceed 1,000 feet. The length of Heroes Tunnel is approximately 1,200 feet with no internal means of egress. Should an internal egress path be installed between barrels for occupants to egress from one barrel to another barrel during an emergency situation, it is essential to provide traffic control to ensure occupancy safety. It would not be safe for occupants to egress into the other tunnel barrel where traffic is moving at full speed.

3.6.1.2 Emergency Signs and Markings for Highway Tunnels

NCHRP Web-Only Document 216, *Proposed Guidelines for Emergency Exit Signs and Marking Systems for Highway Tunnels* proposes the following guidelines for emergency signage and markings systems:

3.6.1.2.1 Emergency Exit Signs

Signs along tunnel side walls should be reflective, photoluminescent, or lighted to indicate direction of travel and distance to two nearest emergency exits.

- General Properties
  - Text and symbol size should be 6 inches in height. Larger symbols are supported.
  - Externally illuminated signs should have 54 lux (f foot-candles) or greater.
  - Internally illuminated signs should have 8.6 candela/m^2 (2.5 foot-lamberts) or greater.

CDM Smith

- Photoluminescent signs should provide 30 mcd/m^2 measured 10 minutes after activating illumination is removed and 5 mcd/m^2 measured 90 minutes after activating illumination is removed.

- Emergency Exit Door Signs

  - Emergency Exit Door signs should be placed on the exit door, or on the tunnel wall immediately adjacent to the exit with the midpoint of the sign no higher than 4.9 feet above the floor. A "running man" symbol should be used in combination with the word "EXIT" in green on a white background as shown below:

Figure 3-3
Sample Exit Door Sign Format
Source: ACCESSIBLEEXITSIGNS.COM

- Emergency Exit Directional Signs

  - Emergency Exit Directional signs should be placed every 82 feet or less along the tunnel wall. If there are exits in two directions relative to the sign location, two signs should be used to provide the respective distances and directions from that location.

  - However, in the case tunnels providing uni-directional traffic flow, the location of the fire would be presumably downstream of a trapped vehicle. Ventilation should move smoke in the downstream direction. In this case, it may be more appropriate to provide uni-directional signage towards the upstream or rear exit of the tunnel as shown below.

Figure 3-4
Sample Exit Directional Sign Format
Source: ACCESSIBLEEXITSIGNS.COM

3.6.1.2.2 Emergency Exit Door Lighting and Markings

- Illumination of Emergency Exit Door

  - Exit doors should have a 6.5 feet area surrounding and including the doorway illuminated 3 to 5 times brighter than the average illumination along that section of the tunnel as measured by a luminance meter.

- Emergency Exit Marking Lights
    - Exit doors should be surrounded with white or clear strobe lights at a flash rate range of 1-2 Hz with a minimum luminous intensity of 150 cd.
- Audible Beacons
    - Audible beacons may be installed to supplement but not replace other means of emergency exit identification. Auditory beacons should contain simple messages which would be calibrated to a decibel level identified through a noise study conducted by an acoustical engineer.

3.6.1.2.3 Exit Path Markings

- General
    - Path markers may be static (marker including a directional arrow) or dynamic (directional/sequential arrays or flashing lights).
    - Dynamic directional markers may be modified remotely if camera coverage, infrastructure, and an available operator are available.
    - Dynamic directional markers should not exceed a flash rate of 2 hz if applicable to minimize risk for epilepsy.
- Location and Spacing
    - Pathway markings should be placed no more than 3 feet above the pathway floor.
    - Exit path lights should be spaced no more than 33 feet apart.
    - Photoluminescent path markers should be spaced no more than 10 feet apart.

3.6.1.2.4 Emergency Messaging

Visual and audible messaging facilitates evacuation for in-tunnel emergencies or disruptive incidents.

- Message Content should provide the following information:
    - Brief description of the event, e.g., “fire in tunnel”
    - Direct instructions for appropriate response, e.g., “walk to exits”

- Dynamic Message Signs (DMS)
  - MUTCD limits length of DMS messages to two sign phases with no more than three lines of text per phase.
  - Each phase must be a separate message, understandable on its own.
  - MUTCD limits messages to 20 characters per line.
  - CTDOT limits messages to eight characters per line.
- Auditory Messages
  - Auditory messages may allow for communication of longer messages than a DMS.
  - An auditory message system consisting of loudspeakers or audible beacons should be studied by an acoustical engineer given the unique acoustical conditions within any tunnel system.
  - Auditory messages may also be sent via radio override or wireless emergency alerts. Cell phone wireless alerts should be restricted to 90 characters or less.

3.6.1.3 Route 15 Expressway Traffic Control

MUTCD and CTDOT standards govern the control of traffic along each Route 15 approach to Heroes Tunnel. Temporary traffic control measures along Route 15 should include traffic diversions, tapered lane closures, and upstream warning devices to encourage driver diversion to alternate routes.

Tapered lane closures on an expressway are designed based on which lane is being closed in addition to the context of other modifications to the travel way and other constraints.

Upstream warning devices should be a ½ mile or more in advance of the tunnel or a temporary traffic control zone according to expressway guidance for Advance Warning Area Section 6C.04. Upstream warning devices may also be placed in advance of alternate routes to better inform drivers. Upstream warning devices may be single static or dynamic signs, a series of static or dynamic signs, or rotating, flashing, oscillating, or strobe lights on a vehicle.

3.6.2 Existing Conditions

Currently, no elements are in place to meet the aforementioned requirements set forth for traffic control in or around the tunnel. Based on the traffic control requirements, the following critical needs were identified:

- Install measures to close tunnel entrances to additional traffic while allowing access to emergency vehicles.
- Install measures to stop upstream traffic prior to the fire site until it is safe to proceed as determined by the incident commander.
- Provide means downstream of incident site to expedite flow of vehicles from the tunnel.

- Define and implement system to allow incident commander to return operations to normal.
- Install additional egress point within tunnel to meet 1,000 feet egress maximum spacing requirement.
- Install emergency signage and markings to facilitate occupant egress.
- Install upstream warning devices in advance of vehicle queues and alternate routes

It should be noted, however, that the original construction of the tunnel did include emergency management features such as traffic lights with flashers as denoted on State Project #185-90 Plan Sheet Numbers 52-54 included in Appendix A.

3.7 Electrical Systems

3.7.1 Standards, Codes, and Evaluation Criteria

Code analysis and recommendations for the power distribution, lighting, and fire and gas detection and signaling systems are based on the following:

- NFPA 37, Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines, 2018 Edition
- NFPA 70, National Electrical Code (NEC), 2017 Edition
- NFPA 72, National Fire Alarm and Signaling Code, 2016 Edition
- NFPA 101, Life Safety Code, 2018 Edition
- NFPA 110, Standard for Emergency and Standby Power Systems, 2019 Edition
- NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, 2017 Edition
- IES RP-8-18, Recommended Practice for Design and Maintenance of Roadway and Parking Facility Lighting, 2018 Edition
- NCHRP Proposed Guidelines for Emergency Exit Signs and Marking Systems for Highway Tunnels, 2017 Edition

Additional evaluation criteria include cost, maintenance, and salvageability of the equipment in the event of rehabilitation/replacement.

3.7.2 Existing Conditions

This section describes the existing power distribution, lighting, and gas and fire detection, alarm, and signaling systems. The architecture of each system is described along with its general condition.

Condition ratings were determined through review of existing plans, inspection reports, and a site visit. During the site visit, the southbound barrel was inspected. It is assumed equipment in the northbound barrel is in similar condition.

Overall, the power distribution is in serious condition due to the ATS (automatic transfer switch) being unreliable, resulting in the possibility of a loss of power to the tunnel. The lighting system is also in serious condition. Light quality is poor and insufficient. The gas and fire alarm systems are nonexistent and are required by code.

3.7.2.1 Power Distribution

The electrical system at the Heroes Tunnel had its last major upgrade in 1984. The electrical service for the tunnel is 600 Amp, 480/277 Volt, 3-phase, 4-wire, connected to two separate utility sources, which are tied through an ATS. CTDOT has indicated that the ATS has not been used in many years and may be non-functional. Refer to Appendix F for the one-line diagram of the existing system.

The preferred ("normal" or typically utilized) utility source is fed from a pole-mounted transformer bank at the end of Manila Avenue in Woodbridge. The service conductors are routed underground from that riser pole to a pedestal cabinet located on the west side of the road near the southbound tunnel exit. The emergency utility source is a pole-mounted transformer bank on Wintergreen Avenue in Hamden. The service conductors are routed underground to a pedestal cabinet on the east side of the road near the northbound tunnel exit. The service conductors are routed underground beneath the Route 15 northbound then southbound lanes. They then stub up on the west side of the southbound tunnel entrance. The conduit continues along the wall through the tunnel, and at the end of the tunnel is routed underground to the other pedestal cabinet on the west side of the road near the southbound tunnel exit. The service entrance equipment within the cabinets was not inspected.

The main pedestal cabinet at the exit of the southbound tunnel contains the power distribution equipment, including the ATS, lighting control equipment, and panelboards which power the lights and miscellaneous electrical loads in the tunnel. The ATS directly feeds a panelboard that contains one 30A nighttime lighting circuit for each barrel. It also has a "Daytime Lights Main" circuit breaker which feeds the daytime lighting panel. In that panel, there are 8 lighting circuits – 4 for each barrel. The daytime lighting panelboard is connected to a remote-control contactor which is controlled by a photo-cell mounted on a rod above the cabinet.

Note that the nighttime lighting panelboard has a circuit breaker which was used to power a panelboard for the equipment in the control room (lights, fans, receptacles, heaters). The fans, transformer, panelboards, heaters, and other equipment were removed from the control room after they were no longer functioning or considered unsafe. From the site visit conducted by CDM Smith it appears the only remaining functional electrical equipment within the tunnel itself are the lighting fixtures.

From the main pedestal cabinet, a single conduit containing the lighting circuit wiring travels along the west wall of the southbound tunnel to its center. It is then routed overhead to a junction box, where southbound tunnel lighting wiring continues to the fixtures, and northbound tunnel wiring is routed in a single conduit through the control room to the northbound tunnel and then on to the fixtures.

Most components of the power distribution system are in poor to serious condition and beyond their useful life. If power from the Manila Avenue feed is lost and the unreliable ATS fails to operate, the tunnels could be left without lighting, which is critical to life safety. The panelboards and other equipment within the pedestal cabinet should be considered priority. The conduit system throughout the facility is in fair to poor condition, with noticeable sagging, corrosion, and cracking. Exposed PVC conduit exists in the tunnels, which is a violation of NFPA 502 Paragraph 12.3.2(2) due to the emission of toxic fumes in event of a fire. Any exposed conduit installed as part of tunnel rehabilitation shall be metallic unless otherwise permitted.

3.7.2.2 Lighting

Record drawings indicate that each tunnel contains 149 linear fixtures mounted on the center of the ceiling. The barrels contain three different types of lighting fixtures, all operating at 480 Volts. The fixtures at the entrance of each barrel contain two 4', 180 Watt (W) low-pressure sodium (LPS) lamps, with some fixtures also containing an additional 55 W lamp for nighttime lighting. The fixtures at the exit side of each barrel contain a single 180 W lamp, with some containing the 55 W nighttime lamp as well. The daytime fixtures are controlled by the photocell above the pedestal cabinet, as described in the power distribution section.

Many lighting fixtures are "out," or non-functional, with either the lamps or ballast having reached their point of failure. Covers are missing on many fixtures, thereby voiding any environmental rating the fixtures originally carried. Luminance (candela/m^2) and illuminance (foot-candle) levels in both tunnels are insufficient and do not meet IES standards. The LPS fixtures also provide poor color rendering, resulting in objects not appearing the same color as when they are illuminated by a natural light source. These factors combine to create an environment where drivers may not be able to properly respond to maneuvers and incidents.

There are no exit signs or egress lighting fixtures or markings within the tunnel.

The conduit system associated with the lighting is in fair to poor condition. Moderate corrosion is visible, and many junction boxes are missing covers, exposing the wiring.

The lighting system is overall in serious condition and should be replaced and upgraded as soon as possible.

3.7.2.3 Gas and Fire Alarm Systems

According to record drawings, the barrels were previously equipped with a carbon monoxide (CO) detection system. This system is no longer present. There are currently no gas or fire alarm systems in the tunnels.

3.8 Emergency Response Plan

3.8.1 Standards, Codes, and Evaluation Criteria

The Emergency Response center in Chapter 13 of NFPA 502 out-lines the planning, coordination and cooperation requires with all participating agencies to fully prepare, train and respond to emergency incidents within the tunnel. The development of an emergency respond plan that anticipates the various emergency incidents that could occur at this facility and identifies the participating agencies and their responsibilities needs to be developed and submitted for approval to the authority having judication. This plan is dependent on the firefighting equipment to be installed within the tunnel and the available equipment of the responding agencies. Liaison personnel from participating agencies shall be noted in the response plan and updated as required with the list reviewed for it to be current at last and every three months (13.6.3). Training and drills are required to be conducted at least twice a year (13.8.4).

3.8.2 Existing Conditions

There is presently not an emergency response plan prepared for an incident at the tunnel. Coordination of service responders and responder readiness for an incident at the tunnel have not been determined.

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Section 4

Engineering Analysis

In order to address the Departments objective to address life safety issues, a set of design fires has been selected to be tested within the tunnel at selected locations. The fire load was created using a set of vehicles in the tunnel. Egress paths are assumed to remain clear for the egress of occupants.

4.1 Philosophy and Objectives

4.1.1 Design Philosophy

The design philosophy for this tunnel is to develop a performance-based solution to reduce or eliminate the need for a mechanical smoke control system. Design fire scenarios were modeled based on worst-case tunnel configurations to ensure tenability is maintained during occupant egress. A simulation where multiple design fires occur at any given time was not considered during this evaluation.

4.1.2 Fire Dynamics Simulator

The Fire Dynamics Simulator (FDS), is a computational fluid dynamics (CFD) model of fire-driven flow. FDS numerically predicts three-dimensional fluid flow with heat and mass transfer across a whole field of cells within a compartment. Smokeview is a separate visualization program that is used to display the results of an FDS simulation. The version of FDS used for this project was FDS 6.6.0.

FDS was developed and is continually upgraded by National Institute of Standards and Technology (NIST) and the Building and Fire Research Laboratory (BFRL). The simulator considers the make-up air velocities and its effects on smoke spread.

FDS defines the tunnel space by rectangular meshes. These meshes are divided into rectangular grid cells. The size and quantity of grid cells affect the model performance and accuracy and therefore should not be too small or too large.

Due to the number of cells and the computation time required for each model it was determined that both tunnels were not required to be modeled, only the one tunnel, in which the fire is located and the smoke is being confined to. This assumption was made based on the requirements of NFPA 502. NFPA 502 requires an exit spacing to not exceed 1000 feet, and currently this is not met. By closing off the two barrels and added an egress corridor this requirement is met. Additionally, with the two barrels closed off, this allows for the smoke exhaust fan and the ventilation fans to work properly within the barrel.

Throughout its development, FDS has been aimed at solving practical fire problems in fire protection engineering, while at the same time providing a tool to study fundamental fire dynamics and combustion.

Hydrodynamic Model - FDS solves numerically a form of the Navier-Stokes equations appropriate for low- speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The core algorithm is an explicit predictor-corrector scheme, second order accurate in space and time. Turbulence is treated by means of Large Eddy Simulation (LES). It is possible to perform a Direct Numerical Simulation (DNS) if the underlying numerical mesh is fine enough. LES is the default mode of operation.

Combustion Model - For most applications, FDS uses a single step, mixing-controlled chemical reaction which uses three lumped species (a species representing a group of species). These lumped species are air, fuel, and products. By default the last two lumped species are explicitly computed. Options are available to include multiple reactions and reactions that are not necessarily mixing-controlled.

Radiation Transport - Radiative heat transfer is included in the model via the solution of the radiation transport equation for a gray gas, and in some limited cases using a wide band model. The equation is solved using a technique similar to finite volume methods for convective transport, thus the name given to it is the Finite Volume Method (FVM). Using approximately 100 discrete angles, the finite volume solver requires about 20 % of the total CPU time of a calculation, a modest cost given the complexity of radiation heat transfer. The absorption coefficients of the gas-soot mixtures are computed using the RadCal narrow-band model. Liquid droplets can absorb and scatter thermal radiation. This is important in cases involving mist sprinklers, but also plays a role in all sprinkler cases. The absorption and scattering coefficients are based on Mie theory

4.1.3 Design Objectives

FDS and Smokeview were used to analyze the tunnel tenability with respect to time, calculate device activation times, and determine ventilation fan size. Studies summarizing the variances for calculations and findings of the FDS simulations are provided in the following sections.

- Performed an initial review of the currently design documents and smoke exhaust calculations to understand the current design and history of the project
- Perform emissions modeling based on parameters to determine expected concentrations of toxic gases in the tunnel due to vehicle exhaust
- Perform multiple fire scenarios to identify the worst-case fire scenario

The design objectives are, based on the Building Code Requirements:

- Protection of occupants
- Improvement of the survivability of occupants
- The structure shall be designed, constructed, and maintained to protect occupants for the time needed to evacuate, relocate, or defend in place

To determine if the tunnel design meets the performance objectives of the NFPA 502, IBC, and IFC; the time in which conditions are considered untenable was defined by the visibility performance criteria defined in the *SFPE Handbook*, 5th Edition. The height of the accumulating smoke layer must be maintained at least 6 feet above any walking surface of the egress path, which is referenced from NFPA 101 and the current editions of the International Building Code. This is to provide tenable conditions for occupants at standing height. The actual code indicates to measure tenability at a height of 6 feet above the walkway but due to the model's configuration the tenability conditions were measured at a height of 6.56 feet, this also builds conservatisms into the model allowing for an additional safety factor.

Visibility was used as the performance criteria because it has been found that once visibility has dropped below the limits set forth in the *SFPE Fire Protection Engineering Handbook* the occupants are less likely to proceed through the smoke to an exit. In addition, visibility will cause the space to become untenable before temperature or CO limits exceed the acceptable limits. A CO limit of 50 ppm has been specified, see Appendix E on determination of CO exposure limits for this facility. This was a limiting factor, along with visibility, and was monitored throughout the tunnel.

Table 4-1 Performance Criteria – Life Safety Tenability

Criteria	US Units	SI Units	References
Temperature	> 158°F	> 70°C	SFPE Handbook
CO Toxicity	> 1200 ppm in Air	> 1200 ppm in Air	National Institute for Occupational Safety
Visibility	≤ 13 feet	≤ 4 meters	SFPE Handbook

Based on the *SFPE Handbook*, documentation by Tadahisa Jin (Table 2-4.2), it was observed that a visibility of 43 feet was required for people who are unfamiliar with the inside geometry of the tunnel as opposed to 13 feet required for those that are familiar with the tunnel. It is our opinion that the occupants within the facility are considered to be familiar with tunnel configurations and the associated egress routes, therefore allowing 13 feet of visibility instead of 42 feet. This assumption is based on the fact that the tunnel egress options are considered to be simplistic. According to the SFPE Handbook, occupants that are egressing in road tunnels tend to continue walking despite low visibility, due to the ability to feel the tunnel wall as they egress. For this reason a 13 feet visibility is the criteria selected.

4.2 Performance Criteria

4.2.1 Occupant Life Safety

The performance criteria for occupant life safety shall be a comparison of the Required Safe Egress Time (RSET) against the Available Safe Egress Time (ASET). The tenability acceptance criteria is based on the *SFPE Handbook* guidelines which provides conditions that shall be maintained so occupants are not exposed to an unreasonable level of safety.

Table 4-2 Degree of Familiarity

Degree of Familiarity Inside of the Space	Smoke Density (extinction coefficient)	Visibility
1.64 ft^{-1}	1.64 ft^{-1}	13 feet

4.2.2 Tenability – ASET

FDS and Smokeview were used to determine visibility within the different fire scenarios throughout the tunnel.

FDS was used to measure the Carbon Monoxide (CO) within the tunnel. Once the threshold of 40 ppm is met, the ventilation system will activate to reduce the amount of CO within the space to maintain it below a limit of 50 ppm. Additionally, FDS was used to measure the visibility, 6.56 feet above the ground level as well as temperature throughout the tunnel.

The ambient outside air temperature used for tunnel was determined to be 104°F, hottest recorded day (1949). A high ambient temperature was used as the worst-case approach because the higher the temperature the more likely the smoke is to stratify, affecting the results of the model. Stratification is the phenomenon where the upward movement of smoke and gases ceases due to the loss of buoyancy.

Visibility throughout the model was monitored using slice files produced by FDS that display the visibility at 6.56 feet above the walking surface, due to the requirement of maintaining tenability 6 feet above the walkway. The visibility tenability limits was evaluated at 13 feet. It is assumed that occupants will begin to egress once fire cues occur. A pre-movement delay has not been determined specifically for tunnels by the SFPE Handbook but based on research pre-movement delays ranged from 27 seconds to 120 seconds. Due to a wide variety of results, no pre-movement delay was used in this report. Occupants travel times were determined based on egress model, but no pre-movement delay was applied.

4.2.3 Egress Calculations – RSET

For the tenability of the space, the objective of a smoke control system is to ensure the atmosphere to which the occupants are exposed does not fall below the tenability limits defined in the performance criteria for the worst-case design fire scenario.

The required safe egress time (RSET) is a sum of the event notification time, occupant delay, occupant movement time, and a margin of safety. An occupant is not expected to begin egressing until notified of an emergency condition (notification time), notification devices located throughout the tunnel will notify occupants to begin evacuation.

According to the *SFPE Handbook* the mean speed occupant's travel on horizontal surfaces is approximately 4.1 feet per second. Once the occupants receive notification to begin evacuation, the occupants are assumed to travel to the nearest exit. Once all occupants have egressed the space, the evacuation time stops.

It is important to note that the conditions within the tunnel in the areas immediately adjacent to the fire may not stay within tenability conditions. The worst-case being a fire in the center of the tunnel, resulting in approximately 200 feet of the tunnel being untenable (16.7% of the tunnel). Tenability unable to be maintained in these areas due to the ventilation system moving the smoke being produced by the fire to a location of discharge. If ductwork was a feasible option tenability would be able to be achieved more efficiently.

4.2.4 Fire Service Life Safety

NFPA 502 requires that conditions be maintained to facilitate emergency operations. The intention is to ensure that regardless of the emergency, the tunnel will not be subject to failure.

The fire protection, life safety, and emergency systems must function to achieve the design results. This includes the ventilation system(s), fire extinguishers, standpipe systems, fire hydrants, etc. In addition, the tunnel structure must be able to withstand the conditions of the fire and remain reliable during the event. This requires heat transfer analysis of the concrete and steel, of which FDS does not produce. An in-depth analysis of the structure is required to ensure the NFPA 502 requirement is met.

4.2.5 Smoke & Toxicity Control

The test criteria for the design and selection of appropriate smoke control systems was to maintain the smoke level at a height of six feet or greater above all walking surfaces and to maintain the CO level to below 50 ppm. The exhaust system will be designed to activate and exhaust smoke and Carbon Monoxide (CO) from the space to maintain tenable conditions.

4.4 Fire Hazard Identification and Design Fires

Given the objectives to address life safety issues, credible design fires have been selected in locations to test the design approach. Based on the configuration of the tunnel it was determined that the fire load that will be present is vehicles located in the tunnel. Egress paths are assumed to remain clear for the egress of occupants.

4.4.1 Fire Hazard Identification

The following identifies the possible ignition sources and available fuel sources within each fire scenario:

Ignition Sources:

- Car Crash
- Vehicle Overheating
- Electrical Short in a vehicle

Fuel Load:

- Vehicle
- More than one Vehicle (single fire location)

4.4.2 Assumptions

This section outlines the main assumptions used to simplify the tunnel system and fire scenarios to enable modelling to be undertaken on a practical level. All assumptions are based on the practice outlined in the SFPE Handbook and practical simplifications have been used to maintain a simple analysis that is representative of a real fire and life safety situation. The assumptions below are applied to all three fire scenarios.

- Only one fire event will occur at any given time.
- No shelter in place provided throughout the tunnel.
- Occupants will become aware of the fire through fire notifications from notification devices within the tunnel, respond to the cue, cope with the cue and egress from the tunnel.
- The two tunnel barrels are separated (based on the assumption that this will have to be closed off to allow for an additional egress path for occupants to meet NFPA 502 requirements) and smoke will not travel from one tunnel to the other.
- It is assumed that the new proposed egress corridor, provided between the two tunnel barrels, is provided, as it required in NFPA 502. This allows for a reduced egress time since occupants do not have to walk the entire length of the tunnel to egress.
- All essential services (fire and other life safety measures) and strategies will be maintained to the operational capacity to which they were designed and correctly functioning during a fire situation as prescribed by the relevant design/installation standard(s).
- All occupants within the structure are assumed to be familiar with tunnels thus the visibility limits within the space must meet or exceed 13 feet up to a height of 6 feet or greater above the walking surface, unless an occupant is able to identify the exit path within the available visibility limits.
- A two car fire size and heat release rate is used for all fire scenarios.
- The soot yield values used for modeling will resemble that of an average mixture of plastic soot yield (.198), for a worst-case assumption.
- The worst-case CO Concentration of car exhaust is applied to the model. As detailed in Appendix E, this assumes that all cars (maximum of 121) are stopped in one barrel at one time. This produces an estimated 2,834 gram per hour of CO emitted in our hour. The volume of one barrel was calculated to be 561,200 cubic feet.
- As detailed in Appendix E the inject rate of 0.0007956 kg/s was used for the FDS modeling. This was calculated using the method below:
  - Tunnel Dimensions of 1,220 feet in length X 28 feet in length X 19 feet in height
  - $2834\ \frac{g}{hour} \times \frac{1\ hour}{60\ minutes} \times \frac{1\ minute}{60\ seconds} = 0.7956\frac{g}{s}$

- $0.7956\frac{g}{s} \times \frac{1\,kg}{1000\,g} = 0.0007956\frac{kg}{s}$

- A total of 22 vents were placed throughout the tunnel as injection points for CO. Each vent had a size of 1 m X 1m resulting in an area of 1 m^2. After dividing the injection rate by the total number of vents the value put into the FDS model resulted in 0.000036164 $\frac{kg}{m^2 \cdot s}$

- This is assumed to be a worst-case assumption for an injection rate of CO. This worst-case assumption was used when analyzing the CO concentration throughout the model, as well as when modeling a fire throughout the space.

- Conversion Rate to PPM: 1 $\frac{mg}{m^3} = 0.873\,ppm$

- Worst Case Results from CDM Smith Model: 178.20 $\frac{mg}{m^3} = 155.55686\,ppm$

4.4.3 Carbon Monoxide (CO)

The tunnel was evaluated without a fire to determine what the exhaust from the vehicles producing CO and to determine the fan size needed to keep the tunnel at tenable conditions for occupants within the space. As discussed under assumptions, the injection rate of 0.000036164 $\frac{kg}{m^2 \cdot s}$ is injected into a total of 22 vents throughout the tunnel. A total of 22 vents was used to disperse the CO throughout the tunnel, similar to a real event. The CO throughout the space, particularly at 6.56 feet above the ground, is monitored to ensure that the CO at the height where occupants would be breathing during evacuation is maintained below the tenability limit of 50 ppm. Exhaust fans for the space were sized in order to achieve 50 ppm throughout the tunnel barrel(during a non-fire event).

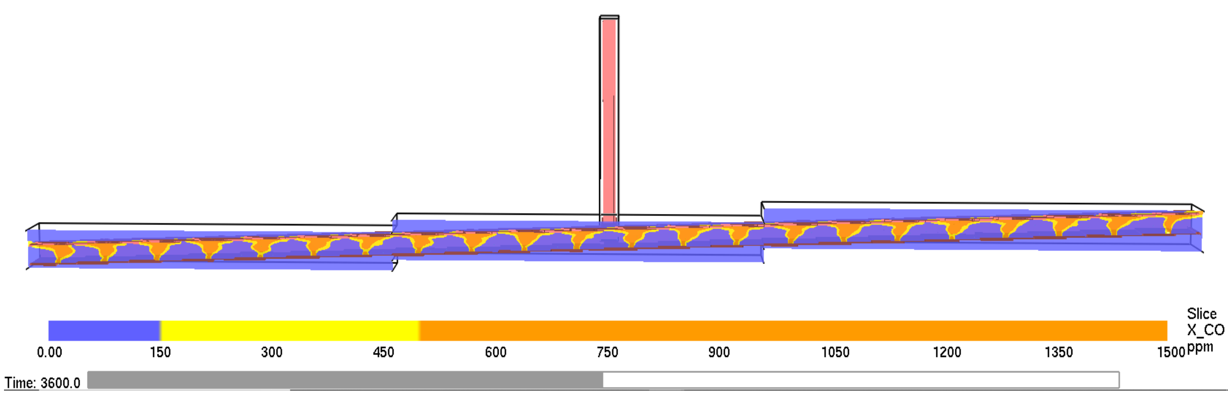

Figure 4-1
CO inject vents injecting CO throughout the Tunnel

CO is a colorless, odorless gas that is released when something is burned. It is roughly the same weight as air, therefore it mixes with air rather than sinking towards the ground. Since exhaust from a car is warm, it causes the CO to rise, but soon it mixes into the air. If there is more than 400 ppm of CO within the air, it can be life threatening within 3 hours. 50 ppm is the OSHA standard for an 8-hour exposure time, and Appendix B.2.2 Air Carbon Monoxide Content also indicates 50 ppm for tenability limit "for the remainder of the exposure." Note that the LRFD Guide Specifications has a more stringent requirement of 35 ppm for 1-hour exposure as indicated in Table 2.8.3.2-1; also see Appendix E for additional information on CO exposure limits for the tunnel.

The natural concentration of CO in air is around 0.2 parts per million (ppm). The main source of additional CO is motor vehicle exhaust and industrial activity. Increased levels of CO reduce the amount of oxygen and may result in vital organs, such as the brain, nervous tissues, and the heart, to not receive enough oxygen to properly work.

4.4.3.1 Carbon Monoxide (CO) Scenario 1

The first scenario that was ran for the CO level evaluation was a scenario that did not have any exhaust provided in the tunnel. The scenario consisted of a total of 22 vents, placed throughout the length of the tunnel, with a worst-case CO inject rate. This rate assumes the cars within the tunnel are running idle with the capacity at a maximum of 121 cars. The CO is injected in the tunnel for a total time of 2 hours and evaluated throughout the tunnel, and specifically at the 6.56 feet above the walking surface.

4.4.3.2 Carbon Monoxide (CO) Scenario 2

The second scenario was used to place CO detectors throughout the tunnel to evacuate the level of CO within the space. The CO is injected at the worst-case scenario rate. An exhaust fan(s) is placed in the center of the tunnel, where the ventilation shaft is located, and begins to exhaust the space once the CO level reaches 40 ppm.

4.4.3.3 Carbon Monoxide (CO) Scenario 3

The third and final scenario was a scenario that consisted of exhaust fans activating, once the CO detector reached a level of 40 ppm. In addition the exhaust fan(s), the CO injection was deactivated at a time of 20 minutes. This was due to an idea of having some kind of notification for occupants that once an incident occurred, occupants would be notified (by a sign or some other signal) to shut off their engines, therefore shutting off CO injection into the tunnel. This is not a code requirement, but a suggestion as a way to reduce the amount of CO being injected into the tunnel.

4.4.4 Design Fires

A total of three design fires were considered for Heroes Tunnel. Ultimately, based on the results from the fire models, fans were sized for the worst-case scenario. The scenarios assume the worst case CO concentration is present during the fire scenarios. The assumptions for all three design fire scenarios discussed in Section 4.4.2.

When a combustible item burns, the heat and combustion products rise in a plume towards the ceiling. As the plume rises, it entrains air, heats the surrounding air and carries it upward to the ceiling. Once the plume reaches a horizontal obstruction, it impinges on the obstruction and spreads in all directions parallel to the obstruction surface. At this point the plume is converted to a ceiling jet. This ceiling jet continues to spread until it reaches the exit of the tunnel or is mitigated by ventilation fans and/or jet fans. The ceiling jet forms a smoke layer which grows in volume and descends towards the floor.

The volume of smoke produced is largely based on the heat release rate (HRR) of a fire and the products being burned. Therefore, it is important to define a fire curve, maximum heat release and fire growth rate profile representative of the fire load in the tunnel. Most fires may be characterized by one or more of these three phases: Growth, Fully-Developed, and Decay phase.

The early stage of a fire is the Growth phase, at this stage the fire has an unlimited supply of fuel and oxygen. The HRR increases exponentially in this phase. The second stage, Fully-Developed phase, begins when the oxygen or fuel supply becomes limited. Once the fuel runs out or the fire department arrives on scene and controls the fire, the heat release rate curves enters the decay phase. The during the decay phase, the heat release rate begins to decrease until the fire burns out or is extinguished.

4.4.4.1 Two Car Fire in Middle of the Tunnel with No Exhaust

Design fire scenario one consists of a two car fire within the tunnel. The fire is assumed to occur in the center of tunnel. Figure 4-2 below shows the heat release rate curve for a two car fire with a peak heat release rate of 6 MW. This data was provided from a report by M.K. Cheong *Design Fires for Vehicles in Road Tunnels.* The report discusses types of vehicles with Peak HRR and how the data was obtained. For the purpose of this tunnel, a car fire was used based on laboratory results. Assuming worst-case, two cars ignite after collision, a peak heat release rate of 6 MW was found after the car burned for roughly 10 minutes. The heat release rate curve shows an additional spike in the heat release rate at a time of roughly 40 minutes, but it is assumed that the fire will be extinguished by this time by the emergency response team.

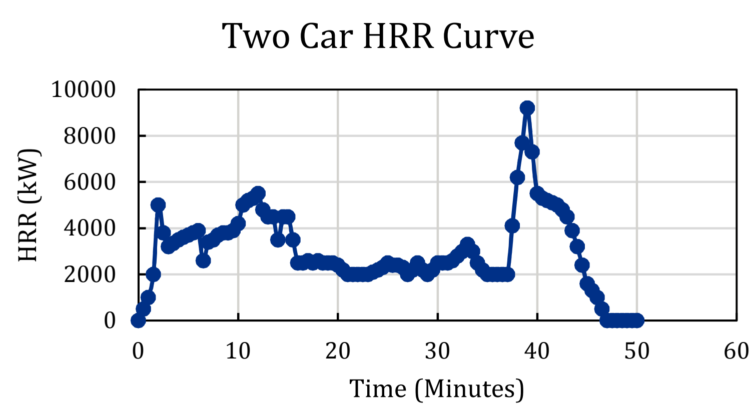

Figure 4-2
Heat Release Rate Curve for a Fire Containing Two Cars

Fire responders will not be evaluated in the scenario, as they have proper equipment to be within the space, during untenable conditions, without causing harm to themselves.

The first fire is a fire located in the center of the tunnel. For scenario 1, no exhaust system is in place. This allows the smoke to fill the entire tunnel quickly, effecting all occupants during egress. Since the tunnel is sloped, this causes the smoke to spread quicker towards the upper side of the tunnel due to how smoke from the fire rises. Additionally, CO is being injected into the tunnel at worst-case conditions with an emissions rate of 2834 g/hour.

The outside air is set to 104°F to resemble a worst-case temperature condition and the soot yield is also set to a worst-case condition of 0.198 (an FDS input). This soot yield results in the space filling up with dark smoke throughout the tunnel.

This scenario does not contain wind to simulate a worst-case condition. If wind was present during the scenarios it would help circulate the air throughout the tunnel and increase visibility for occupants. Wind ultimately results in increased air changes per hour, thus yielding better visibility results.

4.4.4.2 Two Car Fire with Exhaust

Scenario two consists of a fire with the same heat release rate, but an exhaust system is applied to determine if conditions remain tenable for occupants to safely egress the tunnel. For this scenario, first the fire is assumed to occur towards the center of the tunnel, resulting in an egress travel distance of 600 feet for some occupants. Since the fire would be blocking one exit for some occupants, it is assumed that occupant would travel to the other exit for safe egress. This scenario resulted in an egress time of 188 seconds, without any delay time assumed, and therefore would require tenability limits within the space to be maintained for a time exceed 188 seconds.

For this scenario an exhaust system is in place. Since the tunnel is sloped, this causes the smoke to spread more towards the upper side of the tunnel due to how smoke from the fire rises. Additionally, CO is being injected into the tunnel at worst-case conditions with an emissions rate of 2834 g/hour. The exhaust system allows smoke to be exhausted from within the barrel to keep the space within tenable conditions of visibility and CO.

The outside air is set to 104°F to resemble a worst-case temperature condition and the soot yield is also set to a worst-case condition of 0.198 (an FDS input). This soot yield results in the space filling up with dark smoke throughout the tunnel.

The fire placed inside of the tunnel, was based on heat release rate data from a report by M.K. Cheong *Design Fires for Vehicles in Road Tunnels.* The report discusses types of vehicles with Peak HRR and how the data was obtained. For the purpose of this tunnel, a car fire was used based on laboratory results. Assuming worst-case, two cars ignite after collision, a peak heat release rate of 6 MW was found after the car burned for roughly 10 minutes. Other data was provided in the report for heavy good vehicles, motorcycles, and buses. For the purpose of Heroes Tunnel, a two car fire scenario was chosen, based on the types of vehicles that go through the tunnel on average. Wind was not evaluated in this scenario due to a lack of wind data. In the future, it is recommended to evaluate the scenarios with exhaust and ventilation fans including the effects of wind to validate the worst-case scenario.

4.4.4.3 Exhaust/Ventilation Fans in Worst-Case Fire Scenario

After reviewing the results from the first two fire scenarios, it was determined that a fire located at the lowest end of the tunnel is considered to be the worst-case scenario for egress. Appropriate fire protection measures will be added to this scenario in order to maintain tenable conditions for occupants during egress. Since the fire would be blocking one exit, it is assumed that occupant would have to travel to another exit for safe egress. One exit is the other side of the tunnel, and the other option is to egress through the exit corridor into the other tunnel barrel. Although this exit corridor does not currently exist, it was used during egress modeling because this added corridor is a requirement of NFPA 502. This additional exit is required to be added since the spacing between exits cannot exceed 1,000 feet, and the tunnel is 1,200 feet in length.

By placing the fire at the end of the tunnel, this would result in a higher egress time, due to occupants being forced to walk a longer distance to egress the space. Occupants could also egress through the required new egress corridor that allows occupants to egress in the center of the tunnel from one barrel to the other but depending on queuing at the door occupants may choose to walk to entire length of the tunnel rather than waiting to egress through the single door. If this is the case, a traffic control system must be in place to allow occupants to safely egress into the other tunnel without being injured by moving vehicles.

The outside air is set to 104°F to resemble a worst-case temperature condition and the soot yield is also set to a worst-case condition of 0.198 (an FDS input). This soot yield results in the space filling up with dark smoke throughout the tunnel.

The fire placed inside of the tunnel, was based on heat release rate data from a report by M.K. Cheong *Design Fires for Vehicles in Road Tunnels.* The report discuss types of vehicles with Peak HRR and how the data was obtained. For the purpose of this tunnel, a car fire was used based on laboratory results. Assuming worst-case, two cars ignite after collision, a peak heat release rate of 6 MW was found after the car burned for roughly 10 minutes. Other data was provided in the report for heavy good vehicles, motorcycles, and buses. For the purpose of Heroes Tunnel, a two car fire scenario was chosen, based on the types of vehicles that go through the tunnel on average.

Wind was not evaluated in this scenario due to a lack of wind data. In the future, it is recommended to model the scenarios with exhaust and ventilation fans including wind to validate the worst-case scenario.

4.5 Electrical Systems

Overall, each of the power distribution, lighting, and gas and fire detection, alarm, and signaling systems are in serious condition. Components of the power distribution are beyond their useful life but still functional; the unreliability of the ATS is an immediate concern which could result in loss of power to the tunnel. The lighting system has poor light levels and quality, and egress signs do not exist. The gas and fire alarm systems are non-existent.

This section contains further analysis of the condition of each system, along with recommended upgrades and alternatives, based on code compliance, life safety, cost, maintenance, and salvageability.

4.5.1 Power Distribution

Being classified as Category C according to NFPA 502, the tunnel is required to have an emergency power system in accordance with NEC Article 700, which outlines the types of systems which may be acceptable as emergency power sources and the requirements for each. Types of emergency power systems include but are not limited to generator sets, storage batteries (unit-mounted or centralized), separate services, and uninterruptible power supplies (UPS).

Paragraph 12.4.1 of NFPA 502 indicates the systems required to be connected to the emergency power system. They include:

- Emergency lighting
- Tunnel closure and traffic control
- Exit signs
- Emergency communication
- Tunnel drainage
- Emergency ventilation
- Fire alarm and detection
- Closed-circuit television or video
- Fire fighting

The tunnel is currently powered by two separate electrical services. Paragraph 700.12(D) of the NEC reads, "Where approved by the authority having jurisdiction (AHJ) as suitable for use as an emergency source of power, an additional service shall be permitted." Paragraph 700.12(D)(2) adds that "the service conductors shall be installed sufficiently remote electrically and physically from any other service conductors to minimize the possibility of simultaneous interruption of supply." The NEC Handbook notes that "the use of a separate service…requires a judgment by the AHJ…based on the nature of the emergency loads and the expected reliability of the other available sources." These code requirements are to be noted in discussions with the AHJ. It is unknown whether the current arrangement has been approved by the AHJ.

Reusing the existing electrical equipment in the pedestal cabinet to feed new loads is not feasible. There is insufficient space and capacity to accommodate the recommended ventilation equipment. There is also not enough space for new lighting control equipment which would increase system performance and manageability.

New electrical equipment and a different power distribution system arrangement are required for code compliance. A new building will be required to house the new electrical distribution equipment. Existing equipment shall be demolished or abandoned in place as new equipment is placed into service.

4.5.1.1 Proposed Electrical Distribution

The ventilation study has resulted in a total of 8 fans (6 longitudinal jet fans, 2 exhaust fans) being recommended for each tunnel to maintain tenability. An emergency motor control center (MCC) is proposed to house the motor starters for the reversible fans and to power the other emergency loads (lighting, traffic control, communications, fire alarm, and CCTV). A proposed one-line diagram is shown below in Figure 4-3 and in Appendix F.

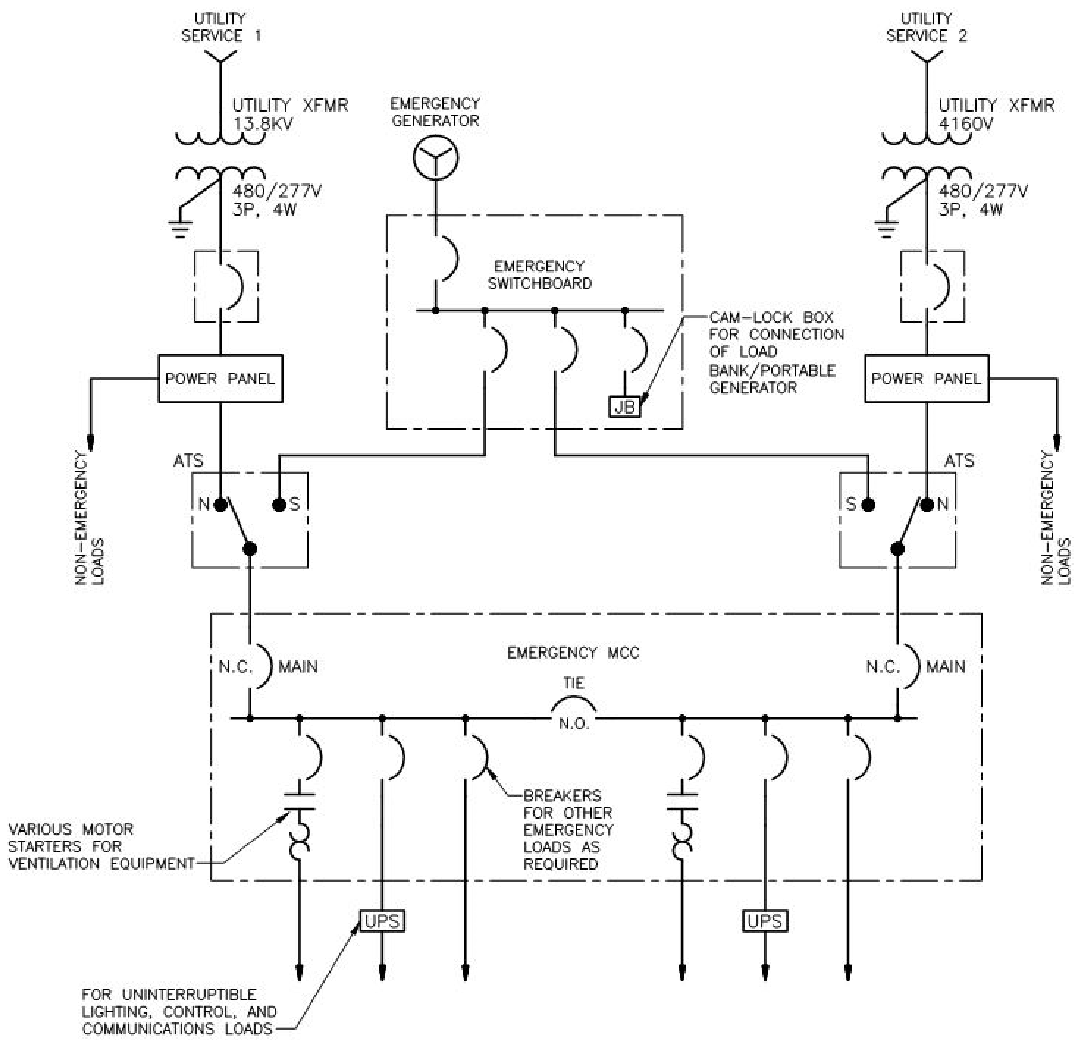

Figure 4-3
Overall Recommended One-Line Diagram

The equipment and electrical services shall be sized to accommodate the maximum anticipated load. The estimated total connected load is 758 kilo-Volt-Amperes (kVA). Refer to Table 4-3 below for a summary of loads.

Table 4-3 Lighting System Criteria

Load Type	Load (kVA)
Emergency Ventilation	641
Lighting	87
Miscellaneous HVAC	20
Miscellaneous Receptacles and Control Equipment	10
Total	**758**

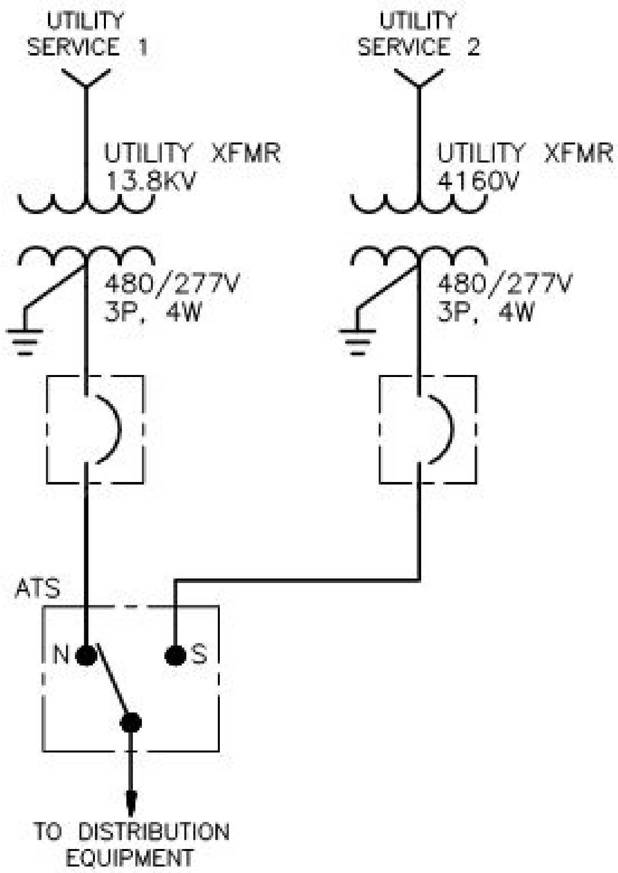

Figure 4-4
Existing Service Entrance

Using only one ATS results in a common point of failure that could result in loss of power to the whole facility, though the risk is reduced by adding bypass isolation. Additionally, NEC 700.5(D) specifies that emergency system "transfer equipment shall supply only emergency loads." Currently, the transfer switch supplies normal loads in addition to non-emergency loads. That use violates the NEC. The NEC also requires specific physical separation of normal and emergency distribution equipment. As illustrated in Figure 4-4 above.

Under the new scheme illustrated in Figure 4-3 above, each of the utility services will be in operation during normal conditions. Each service will supply a separate panelboard that feeds normal (non-emergency) loads in addition to an emergency ATS. The emergency source for each ATS will be a diesel-powered emergency generator set connected to an emergency switchboard.

Each of the ATS's will supply on its load side one end of a main-tie-main emergency MCC with a normally open tie circuit breaker. The emergency MCC will supply all emergency loads. Each bus will supply about half of the emergency loads in each barrel during normal operating conditions, providing even further assurance that life safety does not depend on any one of the three (two utility, one generator) power sources. Note that the entire tunnel lighting system shall be considered part of the emergency system and will be fully backed up. This proposed scheme complies with the NEC's applicable requirements for transfer switches and distribution equipment to be solely dedicated to emergency loads.

Upon loss of a utility service, its associated ATS will signal the start of the emergency generator and transfer to it as the source for that end of the MCC. If the generator fails in addition to one of the utility services, half the fans and lights in each tunnel will still be powered because of the load diversity.

The tie breaker at the emergency MCC will be normally open and manually operated. When maintenance needs to be performed on equipment upstream of either MCC bus, one of the main breakers can be opened and the tie closed for one service to supply the entire MCC during the maintenance. In the unlikely failure of both one utility service and the generator, some devices (fire alarm and other control panels) downstream of the dead MCC bus will be powered by their own battery systems. The maintenance operators/technicians will be able to respond to the incident and, if required, close the tie breaker well in advance of full expenditure of any battery systems. For maintenance, one main breaker can be opened and the tie breaker closed so that one utility service supplies the entire system while still backed up by the generator.

If it is desired to only use one utility service instead of two under normal operating conditions, the main and tie circuit breakers can be kirk-keyed/programmed in coordination with the transfer switches so that the same level of redundancy is still provided

An estimated size of the diesel-powered emergency generator is 750 kW. The rating will be determined during design. The generator must be exercised monthly. Paragraph 8.4.2 of NFPA 110 states, "Generator sets in service shall be exercised at least once monthly, for a minimum of 30 minutes." For this reason, the emergency switchboard shall be provided with a cam lock box that can be used for connection of a load bank for generator exercise. Use of a load bank would permit generator exercise without forcing momentary loss of power to one of the MCC buses.

The proposed power distribution system with redundant utility services and an emergency generator provides superior redundancy, complies with code, and makes efficient use of space.

4.5.1.2 Alternative Electrical Distributions

The generator could be eliminated from the scheme as shown below in Figure 4-5. The scheme is viable, code-compliant, and more simplistic, but it reduces redundancy. It also creates an undesirable common point of failure at the utility services ATS and is not recommended.

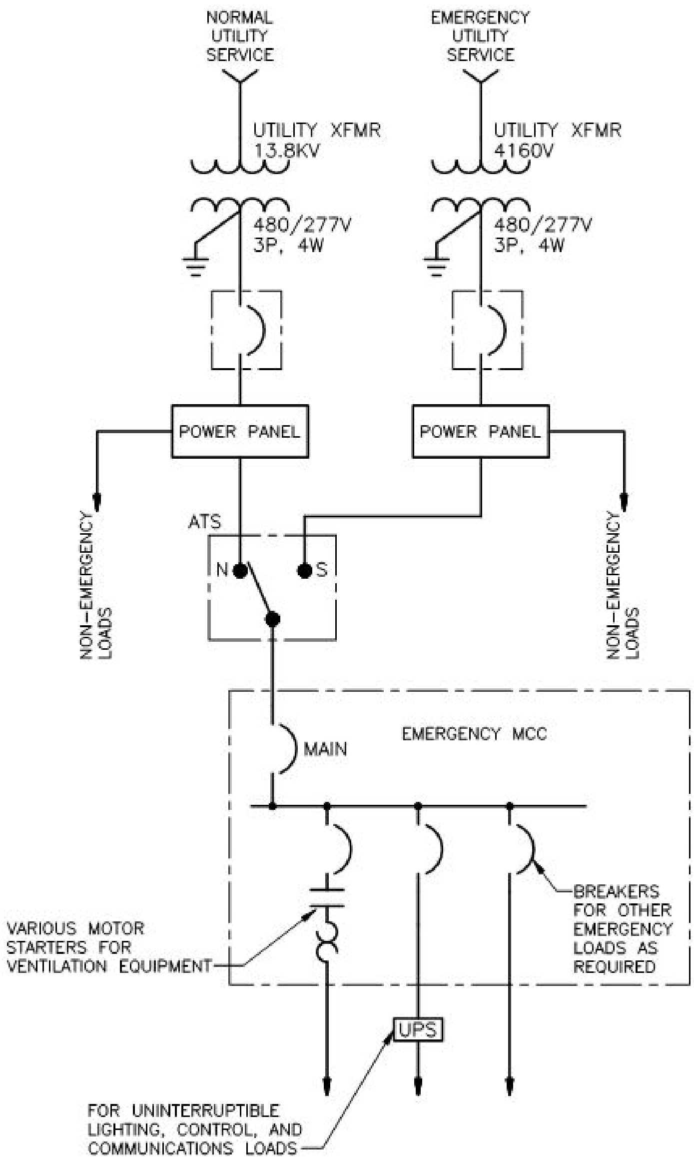

Figure 4-5
Redundant Utility Services Only

Alternatively, both services could feed a main distribution panel through an ATS, with an emergency generator feeding the emergency MCC as shown below in Figure 4-6.

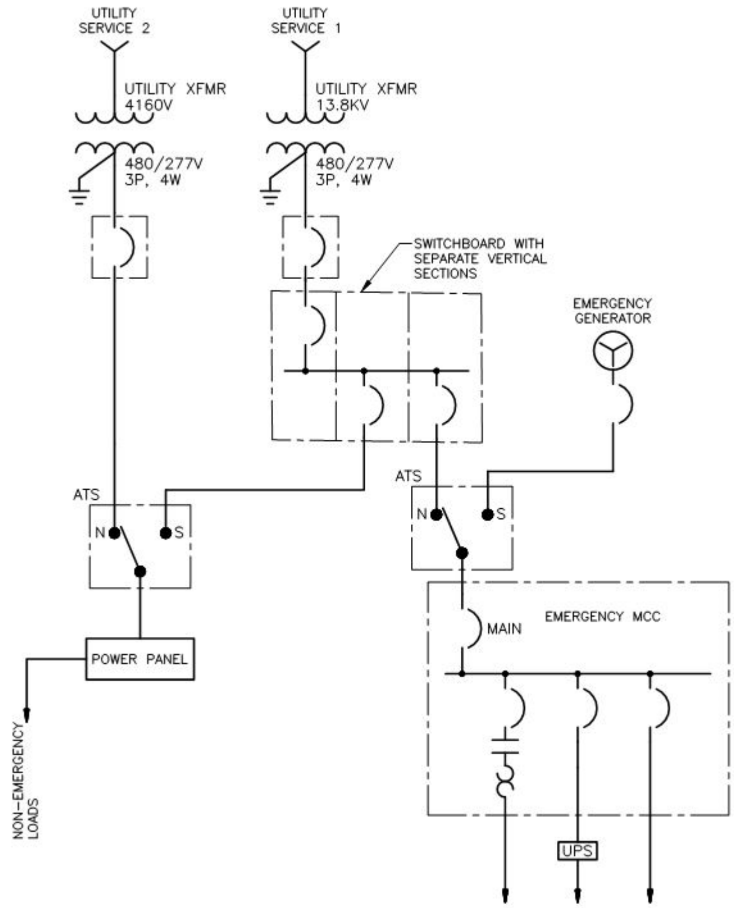

Figure 4-6
Redundant Utility Services and Emergency Generator

Under this scheme, normal loads are powered by one utility service and emergency loads by the other service. It is not recommended. There are other power distribution schemes which may be considered but do not offer the redundancy of the recommended system.

4.5.2 Lighting

The design of tunnel lighting differs from the design of a typical roadway. Because of the length of the Heroes Tunnel, it is considered a tunnel, not an underpass, and supplemental daytime and nighttime lighting is required for drivers to be able to see objects within the structure. It is considered a divided tunnel, with each barrel designated to accommodate one direction of traffic flow. In designing a lighting system, consideration is given to safety, control, energy efficiency, initial capital cost, and ongoing maintenance. The configuration of Heroes Tunnel is presented, and design criteria and system recommendations follow.

Discussion on and recommendations for egress lighting will follow the discussion on the general/ambient lighting within the tunnel.

4.5.2.1 Heroes Tunnel Lighting Topology

The lighting topology of Heroes Tunnel is presented below in Figure 4-7 and in Appendix F.

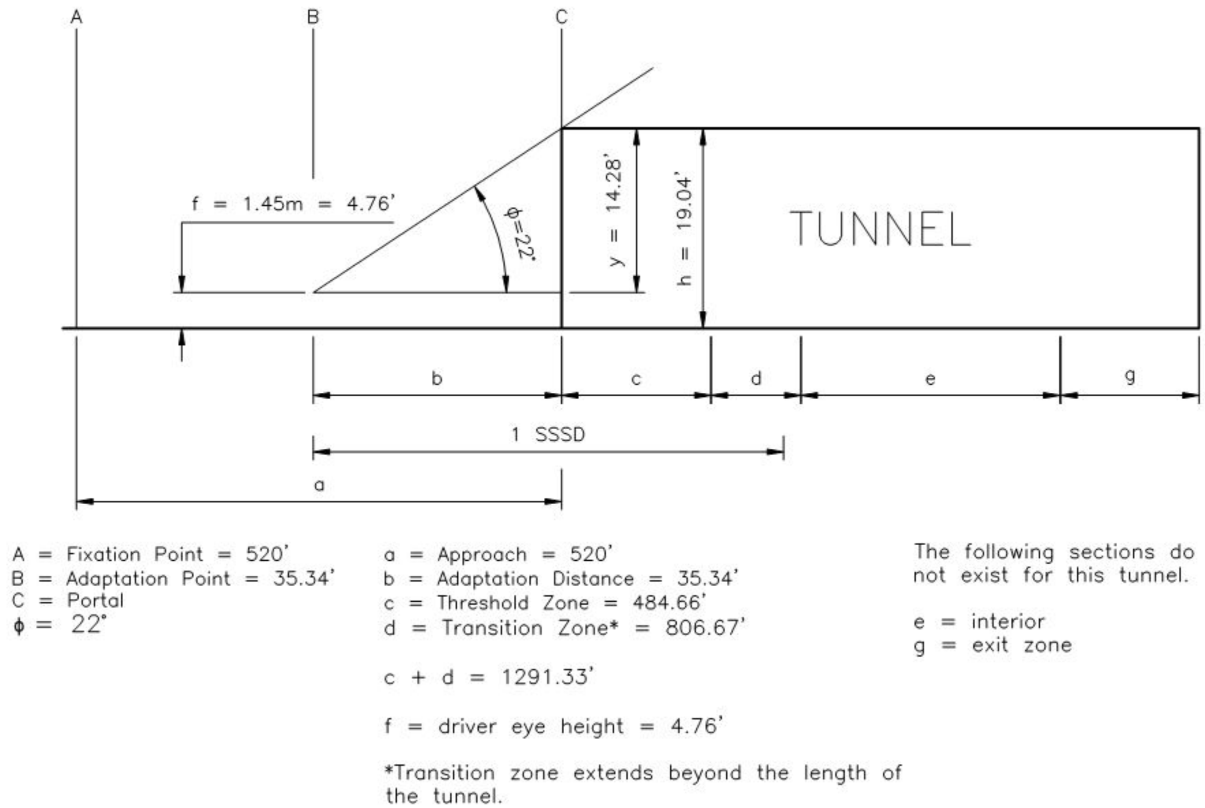

Figure 4-7
Heroes Tunnel Lighting Topology

An explanation of the relevant topology terms is as follows:

- Portal – the entry point of the tunnel
- Approach – the roadway leading to the tunnel – one safe stopping sight distance (SSSD) at 55 mph according to AASHTO
- Fixation point – where the driver fixates on the opening of the tunnel (portal) to identify hazards – one SSSD from portal
- Adaptation point – where the opening of the tunnel becomes the principal feature in the driver's field of view – measured 22 degrees from the driver's line of sight to the top of the portal
- Threshold zone – the first area traveled in the tunnel, where the driver's eyes first adapt from the exterior daytime light levels to the lower levels inside the tunnel – one SSSD less the adaptation distance

- Transition zone – the area after the threshold zone where the driver's eyes have already begun to adapt to the light levels in the tunnel, and the light levels can be incrementally reduced – measured as 12 to 25 seconds of travel time at posted speed. The calculation in Figure 4-7 is based on 10 s of travel at 55 mph
- Interior zone – area after transition zone where eye adaptation is complete – does not exist for Heroes Tunnel based on its length
- Exit zone – where lighting is increased prior to tunnel exit for drivers to readapt to outside levels – not recommended for Heroes Tunnel due to its length

4.5.2.2 Design Considerations

When drivers approach a tunnel during the daytime they are adapted to exterior light levels which are higher than those in the tunnel. The light distributed by interior lighting fixtures cannot compete with the sun or sky, but they can give drivers' eyes time to adapt. Lighting within the threshold zone must provide drivers with luminance that is sufficient for detecting conflicts. If the entrance is too dark, a "black hole effect" is created, and drivers will slow down prior to reaching the portal. Light at the entrance must be bright enough to instill a sense of safety.

As drivers' eyes adapt further in the threshold zone and in the transition zone, light levels can be safely reduced, conserving a significant amount of energy. Selection of type and configuration of fixtures must be performed in conjunction with the specification of a lighting control system capable of dimming fixtures according to their zone. A control system capable of measuring the light levels at the portals and adjusting fixture lumen output accordingly is also recommended.

At night, drivers' eyes are already adapted to low light levels and a constant average pavement luminance is recommended throughout the tunnel. Also recommended at night is pole-mounted approach and exit lighting up to one SSSD that establishes levels no less than one-third that of the interior levels. The lighting control system must be capable of responding to the decreased light levels as night approaches and adjust the interior and exterior light levels accordingly.

A key basis for design of a tunnel lighting system is the required pavement luminance, which is based on the tunnel's shape, orientation, surroundings, materials of construction, posted speed, and average annual daily traffic (AADT).

A typical cross section of the tunnel barrel is shown below in Figure 4-8.

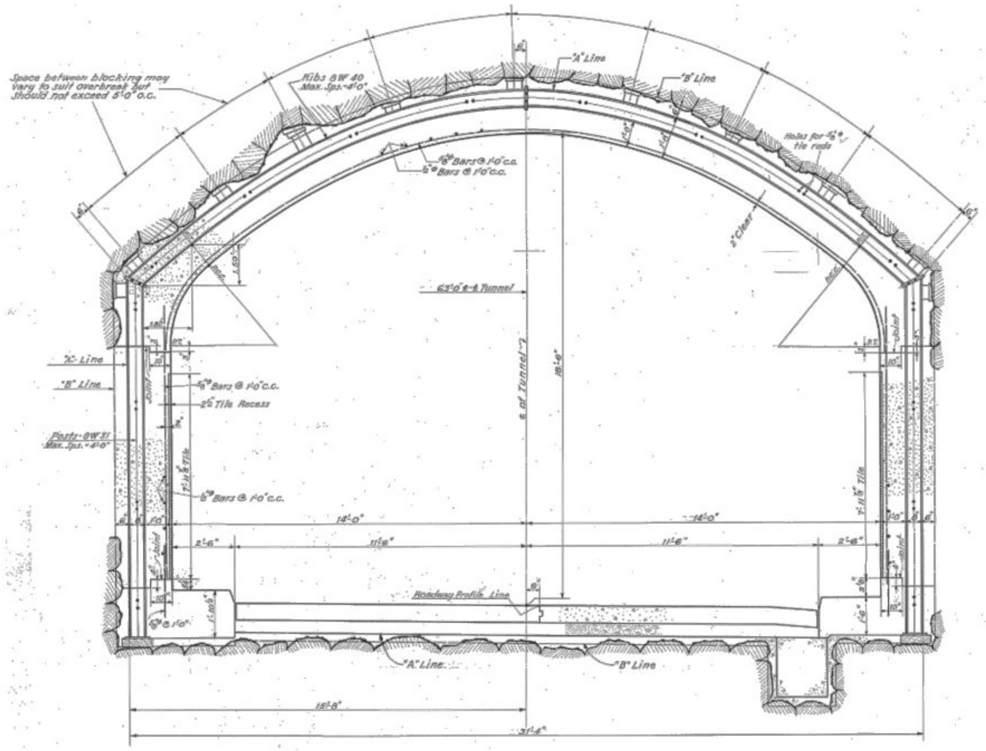

Figure 4-8
Heroes Tunnel Typical Cross Section

The barrel is horseshoe-shaped, 28’ wide, 18’-6” high, with 2’-6” sidewalks on either side of the two 11’-6”-wide lanes. Generally, these dimensions make a linear lighting system along the ceiling centerline optimal. Because the walls are relatively short, a wall-mounted system may not provide sufficient contrast, and because the ceiling is relatively low, providing two mirroring rows on either side of the ceiling is not necessary and is costly.

The OSTA approved speed limit is 55 mph. The average annual daily traffic is approximately 77,000 vehicles. The orientation of the tunnel is nearly southwest to northeast. The presence of West Rock Ridge above and about the tunnel provides some shielding from the sky and sun. Thus, Heroes Tunnel is considered a “mountain tunnel.”

The reflectance values of the tunnel materials are key in establishing the proper design lighting levels. Materials with higher reflectance values both improve the motorists’ perception of the presence of light and also reduce the required fixture output. Heroes Tunnel has asphalt pavement, which has low reflectance. The walls and ceiling are concrete, and they were dirty at the time of the site visit. Therefore, a relatively low reflectance coefficient of 40% was used for the walls and ceilings in proposing a lighting system. Adjustments should made accordingly to the proposed lighting system during detailed design based on any ultimate rehabilitation or change in material to the walls and ceiling. The portals are ashlar stone masonry veneer, which has non-specular and somewhat diffuse reflectance characteristics. It has the benefit of scattering some light at the portal, preventing excessive light from being reflected toward motorists, especially when the sun is at their back.

Other considerations affecting the lighting system are uniformity ratios, fixture light distribution, and environmental ratings. Proper uniformity ratios are key for proper eye adaptation. Regarding light distribution, asymmetrical light distribution for negative contrast (ALD-NC, or "counter-beam lighting") is recommended as it provides high pavement luminance, directs light toward drivers in a controlled manner, and ultimately is most efficient with its lumen output. The frequency of maintenance within the tunnel is not often enough to justify considering any other distribution. Refer to Figure 4-9 below (from IES RP-8-18) for an illustration of counter-beam lighting.

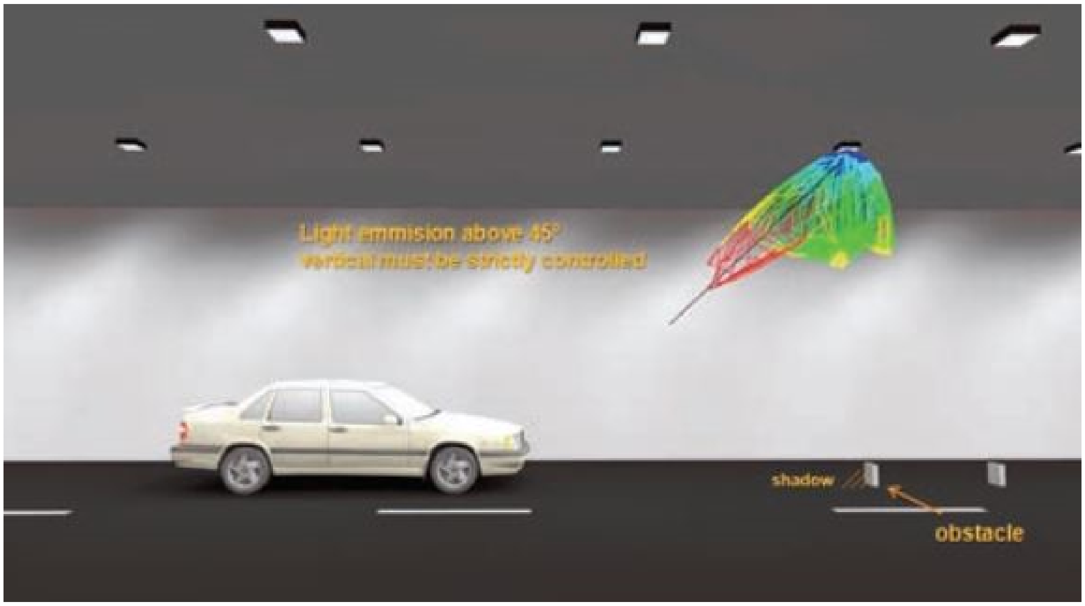

Figure 4-9
Counter-Beam Lighting
Source: IES RP-8-18

For environmental rating, any specified fixture should be rated IP66, meaning it is water-resistant against powerful jets. That rating will allow the fixtures to be washed down during maintenance.

4.5.2.3 Criteria and Proposed Lighting System

For each barrel, a linear fixture arrangement mounted on the ceiling center line is recommended. Fixtures shall be light-emitting diodes (LED), as LED lighting fixtures have superior efficacy (lumens/Watt) and useful life (>100,000 hours) when compared to other light sources. Fixtures shall emit ALD-NC (counter-beam) distribution.

During the daytime, the lighting system shall provide the highest luminance within in the threshold zone near the tunnel's entrance, and the system shall provide incrementally reduced light levels further into the threshold zone and in the transition zone. The current standard, IES-RP-8-18, recommends that the threshold and transition zones be divided further. The recommended criteria for the Heroes Tunnel lighting system are presented below in Table 4-4.

Table 4-4 Lighting System Criteria

Daytime			
Zone	**Avg Luminance (cd/m²)**	**Avg:Min Uniformity**	**Max:Min Uniformity**
Threshold Zone 1 (382')	185	2.0:1	2.5:1
Threshold Zone 2 (103')	130		
Transition Zone 1 (162')	75.3		
Transition Zone 2 (243')	30.1		
Transition Zone 3 (310')	12		

Nighttime			
Zone	**Avg Luminance (cd/m²)**	**Avg:Min Uniformity**	**Max:Min Uniformity**
Length of Tunnel	2.5	2.0:1	2.5:1

Emergency			
Zone	**Avg Illuminance (fc)**	**Min Illuminance (fc)**	**Max:Min Uniformity**
Length of Tunnel	1.0	0.1	40:1 along path of egress

Once criteria are established, several other factors must be considered in selecting fixture type and lumen output. Such factors include environment, life-cycle, and ease of maintenance. Over time, the lumen output of a fixture is decreased. An overall maintenance factor is used to account for the reduction. An analogous term is light loss factor (LLF).

Both dirt depreciation and lamp lumen depreciation (LLD) factor into the LLF. Dirt and debris accumulate on the fixture. To account for this, a dirt depreciation factor of 0.8 is used. Over its life-cycle, a fixture's lumen output gradually decreases, this lamp lumen depreciation. To account for this, the lighting system is designed with lumen output well above the recommended levels. The proposed lighting system will still meet the established criteria after 100,000 hours.

Note that the recommended luminance levels are based on an east-west tunnel orientation. IES-RP-18 recommends slightly higher levels for tunnels oriented North and slightly lower levels for tunnels oriented South. With the initially established levels well above those required, it is sufficient for both directions of Heroes Tunnel to be designed based on the same recommended levels.

Holophane, of Acuity Brands, Inc. was consulted in the development of a lighting layout for the tunnel. Full details for the layout for one barrel, which can be applied to the other, can be found as Appendix F. Refer to Figures 4-10 and 4-11 below for samples of the layout, one near the tunnel entry and one near the exit.

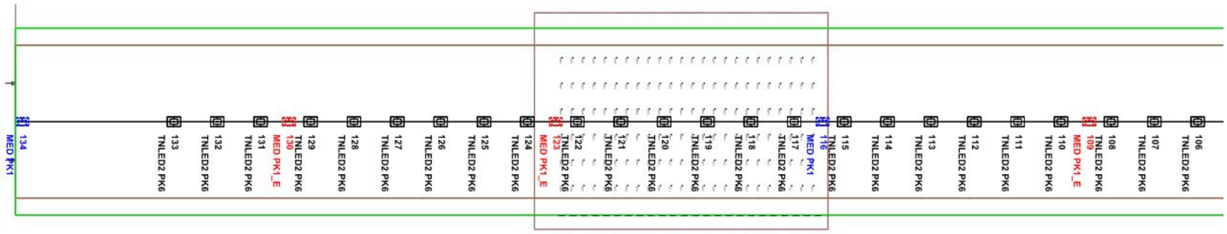

Figure 4-10
Proposed Fixture Layout Near Tunnel Entry

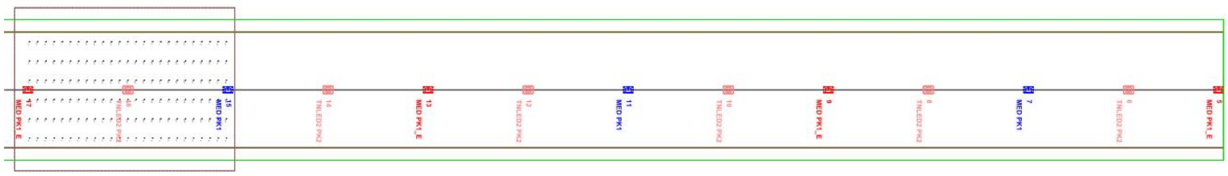

Figure 4-11
Proposed Fixture Layout Near Tunnel Exit

A total of 130 fixtures is proposed for the interior of each barrel. Daytime fixtures are shown in black, green, and pink. Nighttime fixtures are shown in red and blue, with red also denoting emergency fixtures. Nighttime fixtures shall only operate at night. Daytime fixtures near the tunnel entry are spaced 6.5' on-center, whereas daytime fixtures near the exit are spaced 40' on-center.

For each barrel, the approximate lighting load is 43 kW during the day and 2 kW at night.

Only two fixture types are required for the tunnel's interior. They are the Holophane TunnelPass LED Large (TNLED2) and Holophane's TunnelPass LED Medium (TNLEDMED). For daytime fixtures, three different lumen packages of the TNLED2 are used based on the zone; they are also dimmed according to their location. TNLEDMED is used for all nighttime fixtures.

The fixtures are low-profile and fit well within clearance. Their location with respect to ventilation equipment will be coordinated during detailed design. Refer to Appendix F for catalog cutsheets of the fixtures used for the proposed layout.

Nighttime lighting is recommended along the roadway within one SSSD of each tunnel's entry and exit portals. This can be accomplished with four roadside pole-mounted fixtures at each approach and exit. The fixture used in the proposed layout is Holophane's Autobahn Series ATB0.

Note that the possible "flicker effect" associated with motorist discomfort traveling past fixtures between 4-11 Hz is not a concern as the expected travel time through the tunnel is less than 20 seconds.

4.5.2.4 Lighting Control System

Control equipment is required to switch and dim the tunnel LED lighting. Generally, a lighting control panel is required, and control wiring is run alongside the power conductors to the drivers at the LED fixtures. Some methods include using 0-10V analog wiring or using a digital addressable lighting interface (DALI), which utilizes data highway cable.

The lighting control scheme should be able to dim the lighting fixtures according to zone and circuit. It is recommended for the lighting control panel to be able to be programmed for multiple scenes (e.g. daytime, nighttime, maintenance). It is recommended for the system to be capable of receiving remote signals from the maintenance operators/technicians to change the lighting system settings as required. Whether the signal is wireless or hardwired back to a control facility shall be decided during detail design.

Since the luminance at the tunnel portal varies with weather, time of day, and time of year, it is recommended that a luminance photometer be installed one SSSD from each entry portal. The photometer measures the light around the portal and signals the lighting control panel(s) to respond accordingly by adjusting the light levels within the tunnel. It may be feasible for the photometer be installed on the same truss as the traffic information display. Illuminance photometers are sometimes installed within tunnels as well. Because Heroes Tunnel is relatively short, internal illuminance photometers are not necessary.

In developing a proposed control scheme for the tunnel, Nyx-Hemera Technologies, Inc., a partner of Holophane was consulted. Holophane offers fixture-integral Nyx-Hemera local product controllers that communicate with the central lighting control equipment. With the recommended power distribution scheme, two lighting control cabinets and two lighting control network gateways are recommended. Note that instead of using traditional 0-10V wiring, Nyx-Hemera control equipment communicates through a high-frequency signal over the same conductors from which the lighting fixture receives its 60 Hz power. The photometer considered for the proposed system is Nyx-Hemera's LCAM Tunnel Entrance Photometer.

Refer to Appendix F for catalog cutsheets of the equipment considered for the proposed lighting control system.

4.5.2.5 Emergency and Egress Lighting

In addition to the emergency criteria listed in the table above, NFPA 502 also dictates in Paragraph 12.6.5 that "there shall be no interruption of the lighting levels for greater than 0.5 second." It is already proposed to back up the entire lighting system on emergency power. However, there should be another level of redundancy installed to ensure the tunnel is never without lighting. The fixtures shown in red in the proposed layout (spaced 80' on-center) should be placed on UPS in case of the rare failure of the other power sources. The recommended UPS lighting load is only about 500 Watts for each tunnel and would ensure that the tunnels are not without lighting.

Paragraph 7.16.1.2 of NFPA 502 states that "reflective or lighted directional signs indicating the distance to the two nearest emergency exits shall be provided on the side walls at distances of no more than 82'." Exit signs are required at the points of egress. It is recommended for each of these signs to be internally illuminated, and consideration should be given to putting them on UPS power. As a note, wiring for emergency lights and signs is required to be in separate, dedicated raceways per NFPA 502 Paragraph 12.6.3.

4.5.3 Fire Alarm System

Paragraph 7.4.2 of NFPA 502 requires either 24-hour supervision of the tunnel or installation of an automatic fire detection system. Because longitudinal and exhaust fans are required in event of a fire, an automatic fire alarm detection system is recommended to ensure prompt and precise response to a fire. The system shall be installed in accordance with the NFPA 72 and approved by the AHJ.

Paragraph 7.4.8 requires a fire alarm control panel (FACP) to be installed, inspected, and maintained in accordance with NFPA 72. The FACP may be located in the recommended new electrical building. During detailed design, consideration can be given to whether the FACP communicates to dispatch directly or through systems at the control facility.

Paragraph 7.4.6.1 of NFPA 502 requires manual fire alarm boxes to be "installed at intervals of not more than 300 ft and at all cross-passages and means of egress from the tunnel." Heroes Tunnel requires approximately 12 manual fire alarm boxes, the exact number shall be confirmed during detailed design.

Paragraph 7.4.7.4 of NFPA 502 requires automatic fire detection systems to be capable of identifying the location of a fire within 50'. CCTV cameras may be used as part of the automatic fire detection system, but it is not recommended. The precision required to properly operate the ventilation system may not be provided with such a system. Instead, spot-type heat detectors are recommended to be installed every 50', and they "shall be zoned to correspond with the tunnel ventilation zones where tunnel ventilation is provided," in accordance with NFPA 502 Paragraph 7.4.7.6. The location of the fire shall dictate the specific response of the ventilation system, signaling the motor control equipment as required.

Linear type heat detector may also be used. Fiber optic-type linear heat detector cables may be installed in lieu of traditional metallic linear detectors.

Note that per NFPA 502 Paragraph 7.4.7.2, signals for the purpose of evacuation and relocation of occupants within the tunnel are not required when an automatic fire detection system is properly installed and approved.

Carbon monoxide samplers and analyzers will be required for each tunnel, and they will coordinate with the alarm signaling system and the ventilation system control equipment. Carbon monoxide detection equipment shall be connected to an emergency power system in accordance with NFPA 72. Exact location of the equipment will be selected during detailed design.

4.5.4 Miscellaneous Electrical

4.5.4.1 Closed-Circuit Television (CCTV)

The Department may elect to install cameras on the interior and exterior of each tunnel. Required network and server equipment may be installed in the new electrical building, and a monitoring station may be installed at the existing control facility.

4.5.4.2 New Electrical Building

The proposed new building is required to house the new electrical equipment. Installing the equipment in pedestal cabinets and weatherproof enclosures is not practical due to the size and extent of equipment required. The location of the building shall be selected during detailed design, keeping in mind possible tunnel rehabilitation/replacement and West Rock Ridge State Park. The CTDOT District Office is close enough to the tunnel that placing a new electrical building adjacent to the CTDOT District Office would result in only modest conductor upsizing to prevent voltage drop when compared to that required for an electrical building directly next to the tunnel.

4.5.4.3 Miscellaneous Loads, Communications

Network equipment shall be provided within the new electrical building to communicate with the necessary authorities. Separate communication channels will be required for certain legally required signals and other signals.

Power and communications will be required for the lane-use control signal displays.

As a note, power may be brought back to the ventilation building at the top of the ridge for lighting and receptacles if required.

4.5.4.4 Maintenance

Maintenance of electrical and fire alarm equipment within the tunnel shall be scheduled to minimize tunnel shutdowns without sacrificing any equipment integrity. All equipment shall be tested and maintained in accordance with manufacturer's instructions and industry standards. Fire alarm equipment will be required to be tested at least yearly; other electrical equipment may be maintained during the same shutdown. Lighting fixtures may be wiped or hosed down as required. Centralizing electrical distribution equipment within a building allows for easier access and maintenance compared to alternatives.

4.5.4.5 Tunnel Rehabilitation/Replacement

In the event of tunnel rehabilitation/replacement, the electrical distribution philosophy may be similar but further service upgrades may be required. The lighting system layout for a third barrel may differ from that of the two original barrels if it is taller or wider.

Section 5

Engineering Analysis Results

5.1 Means of Egress Evacuation Model

Pathfinder, a model used to evaluate evacuation, demonstrated that if occupants behave based on the assumption that people move away from the fire, people can safely egress the space with the ventilation configuration being proposed.

If a fire is reported in the middle of the tunnel, the exhaust fans will activate and the bi-directional fans will blow the smoke toward the center exhaust shaft. With the fire in the center, people begin to egress toward the exit ends of the barrel toward safety.

If a fire is to occur on either end of the (the entrance or exit of the tunnel barrel) people will begin to egress toward the open end of the barrel that is not blocked by the fire and egress through the center of the tunnel barrel into the other barrel where no fire is present. This new egress corridor being proposed in the center of the tunnel is to meet the code requirement in NFPA 502 for travel distance. During this egress scenario it is important that a traffic control system is implemented to allow for occupants to safely enter the other tunnel barrel and exit safely into traffic. With bi-directional fans activated, occupants are able to egress from the tunnel before tenability becomes untenable.

It is assumed that occupants in the direct vicinity of the fire, where noticeable fire conditions are present, will egress from the area before it becomes untenable. The tunnel, excluding the fire area in the direction of smoke exhaust, remains tenable for the length of the simulation, 20 minutes, as long as the fans and exhaust operate properly and remain active during the length of the scenario.

5.2 Carbon Monoxide (CO)

5.2.1 CO Scenario 1 Results

The results from the first CO scenario verified that some type of ventilation system would be required to maintain the CO within the space below a level of 50 ppm.

This scenario ran for a time of two hours and at a time of 3600 seconds, one hour, the average carbon monoxide (CO) level at 6.56 above the ground is 85 ppm. At the end of the simulation the average the average carbon monoxide (CO) level at 6.56 above the ground is 97 ppm. These exceed the threshold of 50 ppm. It was from this scenario that it was determined that exhaust fans would be required to maintain tenability levels within the tunnel.

5.2.2 CO Scenario 2 Results

Scenario 2 included the use of the center ventilation shaft. By utilizing the center ventilation shaft and exhausting a total of 165,000 cfm the tunnel remained tenable for the occupants below a level of 50 ppm of CO. A total of two 82,500 cfm fans were used to reduce the CO within the tunnel.

In addition, Clarage fans were also tested to determine if they could be used to maintain tenability below 50 ppm for CO. It was determined that a total of 6 fans, per tunnel barrel, at 50,000 cfm could also be used to maintain tenability within the tunnel. The fans were blowing in the direction of traffic and the fans pushed the CO out of the tunnel and kept the tunnel space tenable for the occupants. There is 207 feet between each fan.

5.2.3 CO Scenario 3 Results

Scenario 3 was evaluated based on the same assumptions as scenario 2, but a new assumption was included that occupants would shut off their vehicles to reduce the amount of CO being added to the tunnel. Occupants would be notified via a message provided in the tunnel to shut off their vehicles. This scenario was found to not only reduce the amount of carbon monoxide (CO) being injected into the space, but overall reduce the amount of carbon monoxide (CO) in the space due to the help of the exhaust fans. This scenario was able produce a carbon monoxide (CO) level that is maintained below the threshold of 50 ppm.

In addition, Clarage fans could too be used for this scenario and it would maintain tenability. Once the cars are shut off, the CO stops, and eventually all the CO in the space is pushed out by the 6 Clarage fans placed throughout the tunnel

5.3 Fire Scenario Modeling Results

5.3.1 Fire Scenario 1 Results

Scenario 1 was used to validate that an exhaust system is required to maintain tenability throughout the tunnel. The simulation demonstrated that without a system in place to exhaust the smoke, the tunnel filled in roughly 320 seconds, with the fire located on the South end. See Figure 5-1 below to understand how smoke spreads throughout the tunnel.

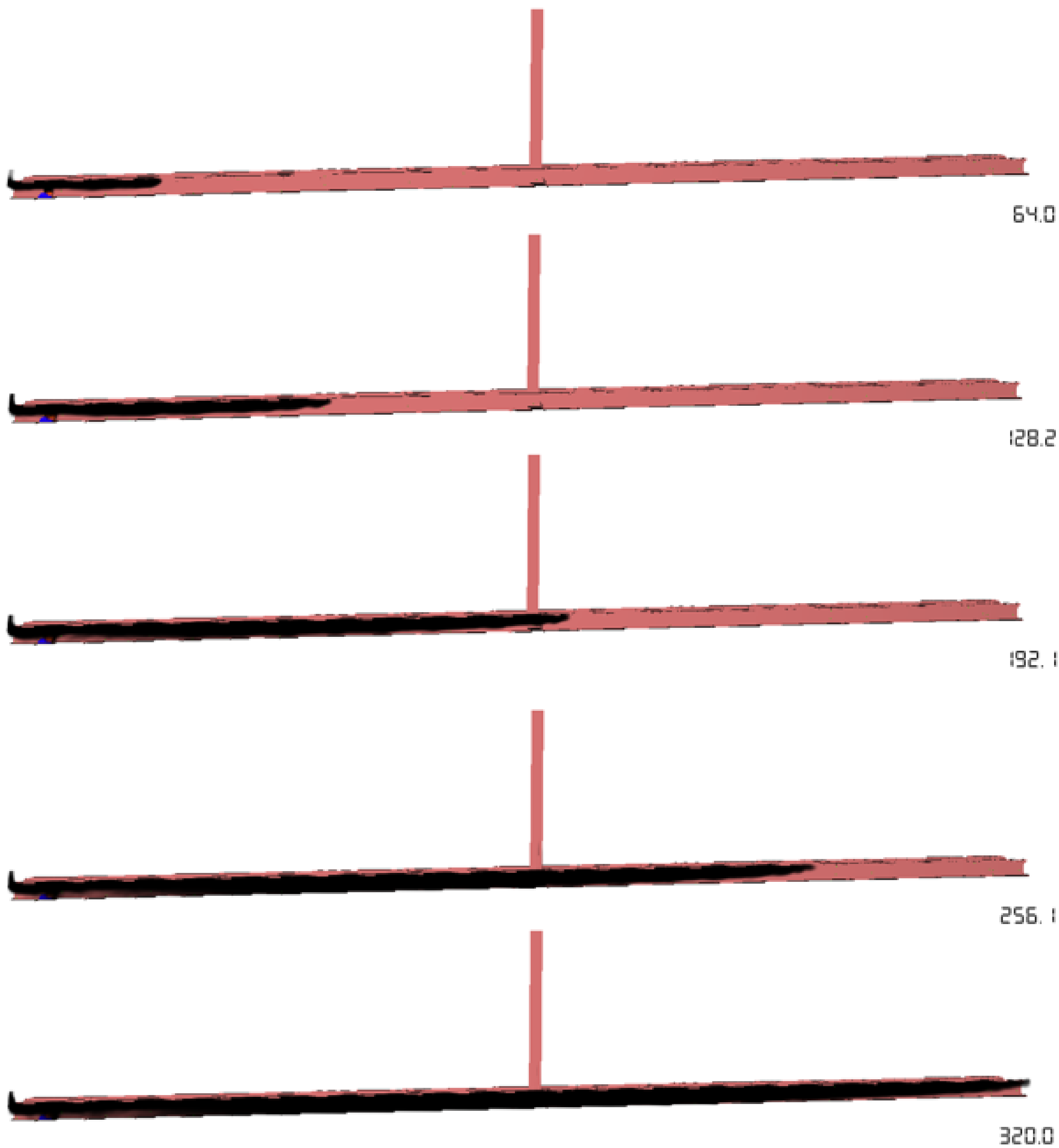

Figure 5-1
How smoke fills the tunnel without exhaust or jet fans in 64 second increments

Based on the fire modeling results of this scenario it is concluded that an exhaust system will need to be present in order to maintain tenable conditions throughout the tunnel.

5.3.2 Fire Scenario 2 Results

Based on the fire modeling results of scenario 2, the exhaust fans were sized to keep the tunnel barrel at tenable conditions, until occupants are able to egress the space. An exhaust fan size of two 82,500 cfm fans was used to maintain tenability within the tunnel for occupants to egress.

With the fire being located at the south end of the tunnel, the exhaust shaft located in the center seemed to pull the smoke throughout the entire half of the tunnel resulting in untenable conditions for a large portion of the occupants. Based on these results, it was concluded that a fire located on the South end of the tunnel would be the worst-case scenario. This scenario determined that the exhaust shaft alone would not keep the conditions tenable for the occupants during egress and an alternative solution is required.

5.3.3 Fire Scenario 3 Results

Based on the fire modeling results of scenario 2 the exhaust shaft alone is not able to maintain tenable conditions. The following ventilation designs were analyzed in the model to determine what size ventilation fans could be used to maintain tenability during the fire scenarios.

- Use of only two central shaft ventilation fans each with 82,500 cfm capacity
- Use of six (6) longitudinal 50,000 cfm jet fans acting in a single direction without the use of the central ventilation shaft
- The use of six (6) unidirectional longitudinal 50,000 cfm jet fans supplemented by the two central ventilation shaft fans.

None of these options met tenability requirements. The alternative that did meet tenability requirements was an automated ventilation system that combined the central ventilation shaft fans with a total of six (6) bi-directional fans in each tunnel barrel with the fans blowing in the direction of the fire. Since the fire was located on the lowest end of the tunnel, the fans would blow towards the low end of the tunnel, blowing the smoke out of the barrel to maintain tenable conditions for occupant egress. Section 5 below discusses the suggested solution to maintain tenability for all fire scenarios.

This scenario resulted in an egress time of 240 seconds, without any delay time assumed, and therefore would require tenability limits within the space to be maintained for a time exceed 240 seconds. This 240 second travel time included occupants egressing through the center exit corridor, as this is a requirement of NFPA 502. The 240 second travel time was the total time it took for all occupants to egress the tunnel. This was considered to be the worst-case egress time throughout the tunnel scenarios

5.4 Electrical Systems

Detailed analysis and justification of the recommended systems is provided in Section 4. Supporting documents are included in Appendix F.

Comprehensive replacement of the electrical systems is recommended because the systems are either not code compliant or well beyond their useful life.

Figure 4-3 in Section 4 illustrates the recommended power distribution system. It is recommended that two utility electrical services are provided to the Tunnel and that they are both operational under normal operating conditions. Both utility services shall supply a number of normal and emergency loads through normal distribution power panels and an emergency motor control center.

The emergency motor control center shall be main-tie-main configuration and shall power all emergency loads required by code. A full list of code-required emergency loads is included in Section 4. It includes but is not limited to tunnel ventilation, lighting, and gas and fire alarm systems. Each MCC bus shall power approximately half of the electrical loads within each barrel.

It is recommended for each utility service to be connected to an ATS that has a generator set as the emergency power source. In case of a utility service failure, the emergency generator shall power the emergency loads normally supplied by that utility service.

The tie circuit breaker at the MCC allows for flexibility of power source selection during maintenance periods and even during normal operating periods.

Because of the tunnel's geometry, a centerline ceiling mounted lighting system is recommended. LED lighting systems provide optimal light distribution, efficiency, and controllability. The type, spacing, and lumen output of the lighting fixtures shall be controlled according to their location within the tunnel, the time of day, and the specific exterior lighting conditions at any given point during the day. Counter-beam lighting is recommended, as it is most efficient in distributing light that allows motorists to properly respond to conflict.

It is recommended for the entire tunnel lighting system to be backed up on emergency power. Select lighting circuits shall be backed up on UPS so that it is virtually guaranteed that the tunnel is never without illumination.

A lighting control system consisting of control cabinets and local fixture controllers is recommended to control the output of the fixtures. A luminance photometer shall be provided at the approach to each tunnel to measure the amount of light present and allow the control system to control output accordingly.

Internally illuminated egress signs shall be placed throughout the tunnel according to the distance required by code and at all points of egress.

A fire alarm system shall be installed within the tunnel in compliance with code and in coordination with the recommended ventilation system. Manual fire alarm pull boxes and spot-type heat detectors shall be installed at code-required distances. Carbon monoxide probes and analyzers are recommended to be installed. Activation of gas or fire alarm detection devices shall result in activation of the ventilation system according to the location of detection.

Alarms and signals shall be communicated with the appropriate parties (e.g. Fire Department, CTDOT) through either hardwired or wireless signals as required.

A building or other climate-controlled structure is recommended to house all the power distribution, control, and networking equipment.

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Section 6

Recommendations

6.1 Fire Detection

6.1.1 Fire Alarm System

Fire alarm systems are intended for life safety and should be design, installed, and maintained to provide indication and warning of abnormal unsafe conditions. This system should alert occupants and summon appropriate aid in adequate time to allow for occupants to travel to a safe space. The fire alarm system should be part of the life safety plan that includes a combination of prevention, protection, egress, and other features particular to that occupancy.

Instead of smoke detection throughout the tunnel, Gas detectors are suggested in order to monitor tenability throughout the space. It is our recommendation that once the gas detectors reach a specific threshold (such as 40 ppm of CO) a signal would be sent to the ventilation system to prevent the space from reaching great than 50 ppm of CO within the space. Gas detectors, linear heat detection, or flame detection systems will be used for the fire alarm system. Additionally, manual means of detection are suggested, such as manual fire alarm pull station every 300 feet. This would be beneficial for occupants egressing the tunnel to notify others of an evacuation emergency. Once the pull station is activated strobes placed throughout the tunnel would activate to notify others to begin evacuation. This suggestion is a method to get occupants to begin evacuating the tunnel earlier.

6.2 Means of Egress

In order to meet the requirements of NFPA 502 and to allow for safe evacuation for occupants during an emergency situation, it is recommended to add an egress corridor from one tunnel barrel to the other. See Figure 6-1 illustrating the layout being proposed and the alternations required to the existing central control room to form an egress corridor. The corridor shall have fire doors on both sides of the egress corridor to provide adequate separation and with proper traffic control installed the travelway can be used as an egress pathway.

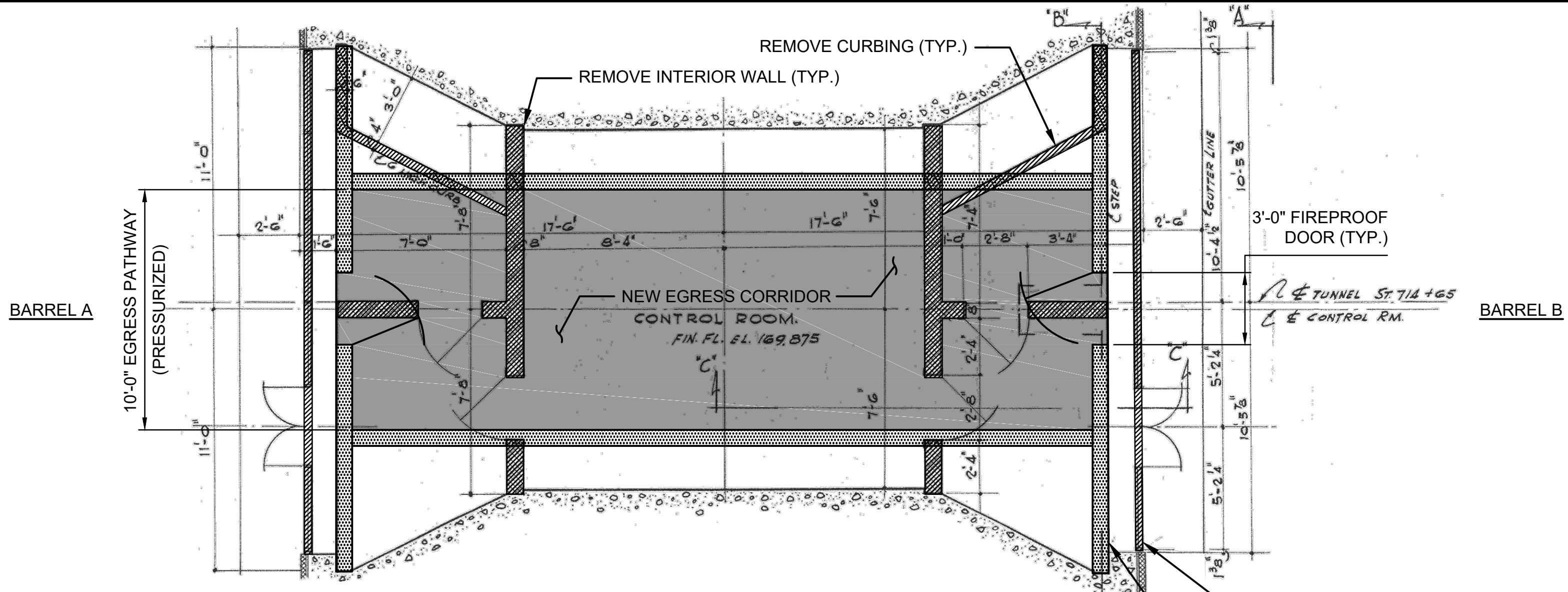
6.3 Fire Protection

6.3.1 Automatic Fire Sprinkler System

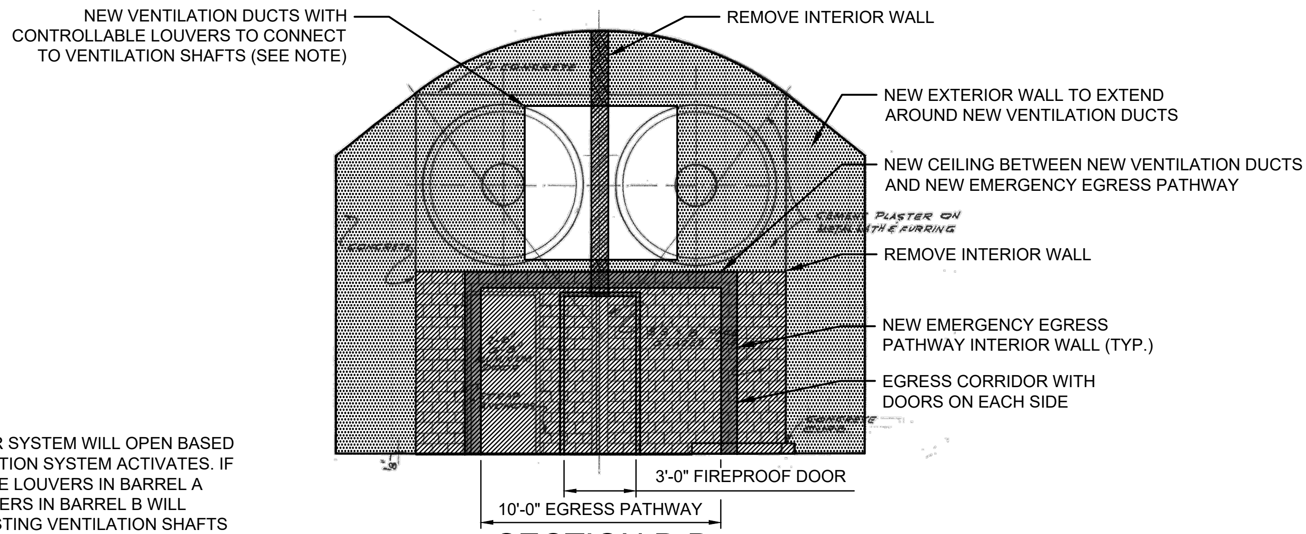
It is our recommendation, based on the results from the fire modeling, that no automatic fire sprinkler system will need to be provided throughout the tunnel. With the other fire safety measures in place, such as a smoke ventilation system, an additional egress route, and adding standpipes that the tunnel remains tenable for the occupants during the time of egress.

6.3.2 Smoke Ventilation System

After running multiple CO testing using FDS, it is our recommendation to use Clarage fans once the CO level reaches 40 ppm. If after 5-10 minutes the CO level with the tunnel is not reduced, it is recommended to activate the exhaust to ensure the CO level does not reach 50 ppm and cause



CONTROL ROOM PLAN



SECTION B-B

NOTES:
NEW ELECTRONIC LOUVER SYSTEM WILL OPEN BASED ON WHICH BARREL DETECTION SYSTEM ACTIVATES. IF BARREL A IS IN ALARM, THE LOUVERS IN BARREL A WILL OPEN AND THE LOUVERS IN BARREL B WILL REMAIN CLOSED. THE EXISTING VENTILATION SHAFTS COULD BE USED FOR ANY EVENT.

CDM Smith

Figure No. 6-1
Control Room Plan

harm to the occupants within the tunnel. These fans will be activated by Gas Detectors located throughout tunnel.

Based on the worst-case scenario without ventilation, a system is required to maintain tenability conditions throughout the tunnel. It is proposed to incorporate a ventilation system to maintain the tunnel at tenable conditions for occupants. Based on the worst-case fire modeling results, in a total ventilation capacity of 165,000 cfm (two 82,500 cfm fans or four 41,250 cfm fans) are suggested. In addition to the exhaust shaft being used, bi-directional jet fans placed at the ceiling of the tunnel are also being proposed.

The ventilation system being proposed is to be located in the center of the tunnel using the existing ventilation shafts in addition to the bi-directional jet fans being proposed consists of 6 fans per tunnel barrel at 50,000 cfm per fan, resulting in a total of 12 jet fans. The fans are spaced approximately 207 feet apart.

In order to ensure that the ventilation system and jet fans operate correctly, our recommendation is to complete concrete surface repairs to spalls and cracks within the ventilation shaft and grout the joints to eliminate the contact between ventilation shaft and groundwater. This will reduce the effect of the freezing and thawing of groundwater and eliminate the icicles during winter, which could result in damage to newly installed fans. Also, we recommend separating the two tunnels by closing off the wall that connects the two tunnels to allow complete separation between the two. This will allow the ventilation shaft and jet fans to properly remove the smoke within the barrel. The fire models were model as separate spaces, similar to if a wall was added to prevent smoke and air from moving back and forth between barrels.

By completing the fire modeling with multiple scenarios, it was determined that an alternative would need to be considered. A zoning method is proposed to help maintain tenability throughout the tunnel. Our proposed solution is to have bidirectional fans and update the existing shaft with new exhaust fans to maintain tenability. If the fire is detected on the lower South end of the tunnel, the ventilation fans shall be programmed to blow towards the left end. If the fire is detector on the upper North end of the tunnel, the ventilation fans shall be programmed to blow toward the right end. The exhaust would not activate in these scenarios. See diagrams below for an explanation.

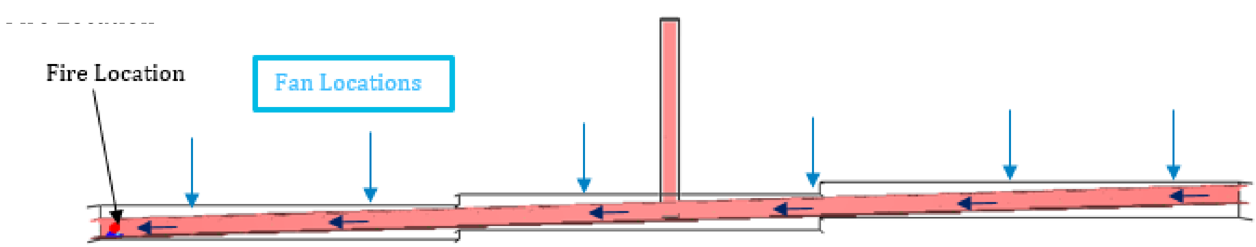


Figure 6-2
Fan movement for a fire located in Zone 1 (South Portal End)

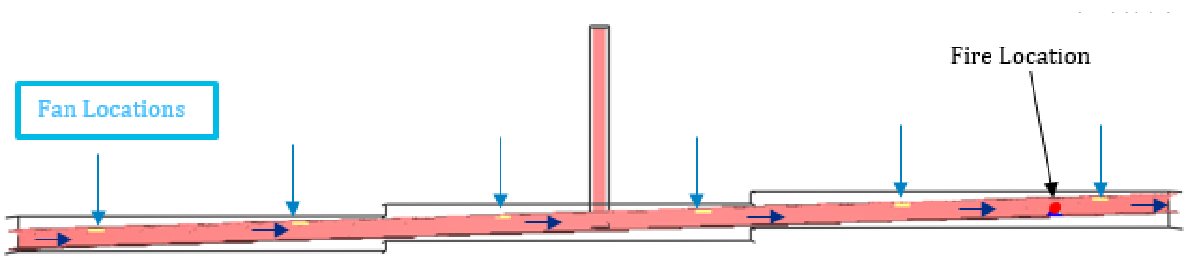


Figure 6-3
Fan movement for a fire located in Zone 3 (North Portal End)

If a fire was located in the center of the tunnel the exhaust would activate and the ventilation fans would blow towards the exhaust shaft. See diagram below.

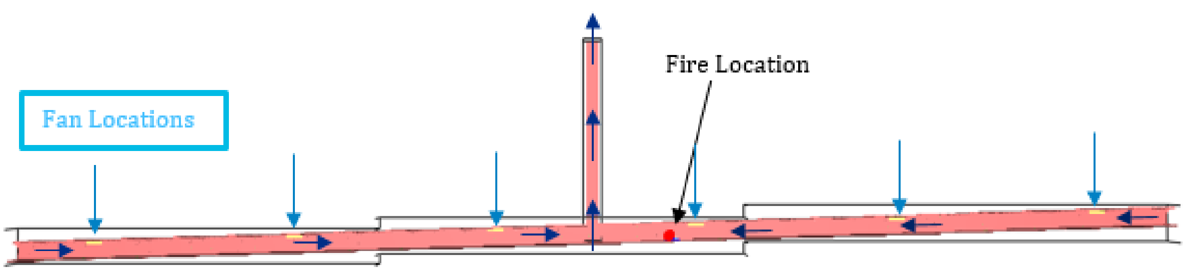


Figure 6-4
Fan movement for a fire located in Zone 2 (middle) with Exhaust

In order for this configuration to work zones must be setup to activate based on Gas Detection. The fan manufactures and mechanical engineers will need to work together to program the zones to activate accordingly, depending on the fire location.

Based on the results of the performance-based fire modeling shown above the configuration as presented below is sufficient to allow adequate egress of occupants. Some sort of detection system will need to be in place to activate the correct fan direction and activate the exhaust shaft. A few options can be considered for fire detection such as gas detection, heat detection, or flame detection. Detectors shall be located throughout the tunnel in accordance with the requirements of NFPA 502. Although the visibility within the tunnel drops below the tenability criteria of 13 feet it is assumed that due to the height of the tunnel it is not possible to achieve tenable condition within the direct vicinity of the fire. In summary, the current tunnel requires a smoke control system to maintain tenability conditions throughout egress, ASET > RSET, the current natural ventilation created by the open ends of the tunnel does not provide adequate ventilation. Below is the proposed configuration to maintain tenability throughout the space. It should be noted that the mechanical engineers and the fan manufacture are to program the exhaust fans and ventilation fans to activate in a zone gas detection configuration.

Zone 1 Fire:

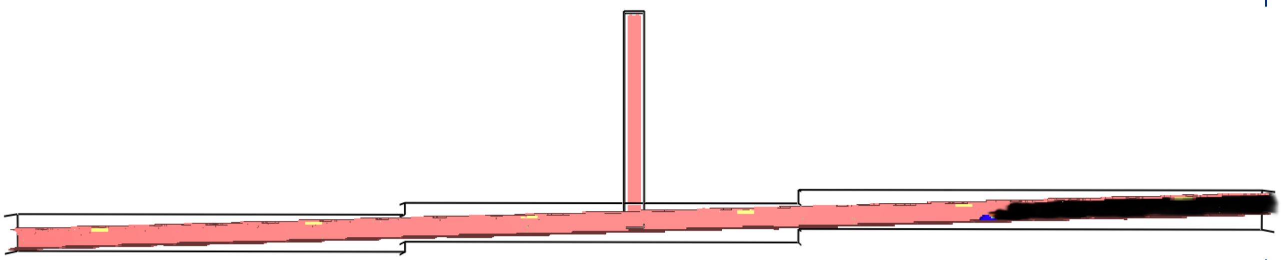


Figure 6-5
Fire Located in Zone 1 (South end) with Jet Fans

Zone 2 Fire:

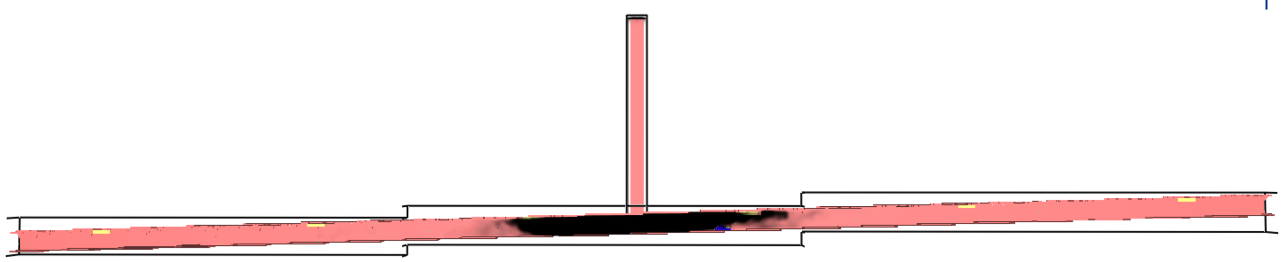


Figure 6-6
Fire Located in Zone 2 (middle) with Jet Fans and Center Exhaust

Zone 3 Fire:

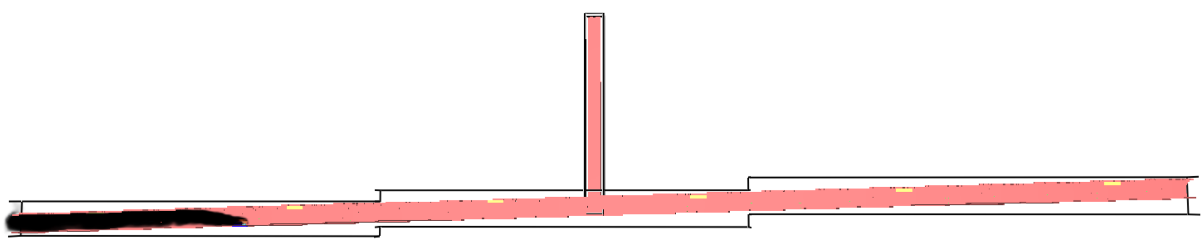


Figure 6-7
Fire Located in Zone 1 (North end) with Jet Fans

6.3.3 Fire Department Connections (FDC)

In order for the fire department to fight a fire within the tunnel standpipes need to be installed, as required by NFPA 502, every 275 feet. The system shall be installed in accordance with NFPA 14 and inspected and maintained in accordance with NFPA 25. With the water supply available for the fire department, controlling a fire within the tunnel will be a manageable task.

Currently, three fire hydrants are near the location of the tunnel, but none are within 100 feet of the tunnel entrance or exit points. This would result in limited resources for the fire department. See Figure 3-2 which illustrates the existing hydrant locations.

Adding a total of 5 standpipe connections within each tunnel barrel, to meet NFPA 502 and NFPA 14 code requirements is proposed. A layout of the proposed standpipe locations is illustrated previously in Figure 3-1. The standpipes are spaced with a travel distance of not greater than 275 feet between each standpipe connection. Each standpipe location requires two fire department connections.

In addition to the standpipes, two new fire hydrants are proposed for the tunnel. In order to meet the requirements of NFPA 14, section 6.4.5.4, a fire department connection shall not be located more than 100 feet from the nearest fire hydrant. With the current layout of the fire hydrants, this requirement cannot be met. We propose adding two new fire hydrants, one to each side of the tunnel. The location of the new proposed hydrants and a drawing of all hydrant locations in proximity of the tunnel can be found in Figure 3-1 of the report.

6.4 Fire Protection of Structural Elements

The Heroes Tunnel is a Category C facility that is subject to the specific requirements stipulated in NFPA 502, Section 7.

Concrete has excellent inherent fire-resistivity properties. However, concrete structures must still be designed for fire effects. Structural components need to withstand dead and live loads without collapse; rise in temperature causes a decrease in the strength and modulus of elasticity for concrete and steel reinforcement. In addition, fully developed fires cause expansion of structural components and the resulting stresses and strains must be resisted. Therefore, maintaining temperatures to limit specified in code may not adequate prevent progressive failure.

Without physical testing of the concrete liner to ascertain material properties and asses material condition, and, without performing computational fluid dynamic (CFD) modelling and numerical structural analysis that accounts for material property changes, it is difficult to quantify performance of the existing structural elements subjected to elevated temperatures to meet current NFPA 502 requirements.

To that end, it is recommended that the following steps be taken:

- Evaluate and quantify existing structural element properties
- Run CFD modeling that capture temperatures within the tunnel during anticipated fire events
- Run numerical analysis to evaluate the performance of the structural elements subjected to reduced material and strength properties due to anticipated fire events
- Identify structural elements that would likely result in progressive failure of the facility due to the anticipated fire events
- Develop minimal rehabilitation requirements that would eliminate and/or manage the risk of progressive failure of the structural elements

6.5 Traffic Control

As identified under Section 3.6.2 Existing Conditions, the critical traffic control needs to address are:

- Install measures to close tunnel entrances to additional traffic while allowing access to emergency vehicles.
- Install measures to stop upstream traffic prior to the fire site until it is safe to proceed as determined by the incident commander.
- Provide means downstream of incident site to expedite flow of vehicles from the tunnel.
- Define and implement system to allow incident commander to return operations to normal.
- Install additional egress point within tunnel to meet 1,000 feet egress maximum spacing requirement.
- Install emergency signage and markings to facilitate occupant egress.
- Install upstream warning devices in advance of vehicle queues and alternate routes

The following passages recommend measures to address the critical traffic control issues.

6.5.1 Close Tunnel Entrances to Additional Traffic

To facilitate closure of the tunnel entrances to additional traffic while maintaining access to emergency vehicles, lane-use control signals should be installed at each portal entrance and at a location where it is desirable to stop vehicles along Route 15. Optionally, this secondary signal may be located at an upstream location which may allow for access to highway crossover.

Due to the potential length of queues resulting from an incident inside the tunnel, the area controlled by the lane-use control signals may extend significantly. According to the MUTCD, lane-use control signals shall be located such that road users will at all times be able to see one signal indication over a distance of up to 2,300 feet. A separate traffic study can model estimated queue lengths to determine a recommended design placement of multiple lane-use control signals, if necessary.

Remote management from a traffic operations center would allow for the most responsive management of these lane-use control signals.

6.5.2 Control Upstream Traffic Prior to Fire Site

Vehicles already downstream of the lane-use control signals at the time of the incident but still upstream of the fire site should be managed by both Dynamic Message Signs and auditory messages.

Dynamic Message Signs should be installed at intervals within the tunnel to create partitioned sections. An operator can identify the sections of the tunnel which would require specific messages and activate the relevant DMS messages accordingly. Remote identification of the fire location relative to DMS locations would require a camera monitoring system, such as a Closed

Caption Television (CCTV) system. In the event of a fire, thermal imaging camera systems may improve remote emergency identification as visibility of fire and tunnel occupants is not reduced by smoke or light glare.

Remote management from a traffic operations center would allow for the most responsive management of the DMS and auditory messages.

6.5.3 Facilitate Traffic Flow Downstream of Fire Site

Vehicles already downstream of incident may continue to exit the tunnel. Should it be determined by the incident commander that vehicular flow may continue adjacent to the incident, traffic control may be managed by both Dynamic Message Signs and Auditory Messages.

Proper identification of the fire location relative to DMS locations would require a camera monitoring system, such as a Closed Caption Television (CCTV) system. An operator can identify the sections of the tunnel which would require specific messages and activate the relevant DMS messages accordingly. In the event of a fire, thermal imaging camera systems may improve remote emergency identification as visibility of fire and tunnel occupants is not reduced by smoke or light glare.

Remote management from a traffic operations center would allow for the most responsive management of the DMS and auditory messages.

6.5.4 Return to Normal Operations

An established incident commander must have an emergency protocol plan including fire and police emergency contacts along with a direct line of contact with the traffic operations center managing traffic control monitoring and response. Through coordination with these entities, the incident commander may determine the appropriate time to return operations to normal.

6.5.5 Additional Egress Location

As noted previously, Heroes Tunnel does not meet the requirements for egress locations. The length of Heroes Tunnel is approximately 1,200 feet with no internal means of egress. NFPA 502 requires that exits for protection of tunnel occupants not exceed 1,000 feet spacing.

An internal egress path must be installed between barrels for occupants to egress from one barrel to another barrel during an emergency evacuation. A door adjacent to the control room may be installed to provide egress between barrels. The figure below is an example of a potential egress path.

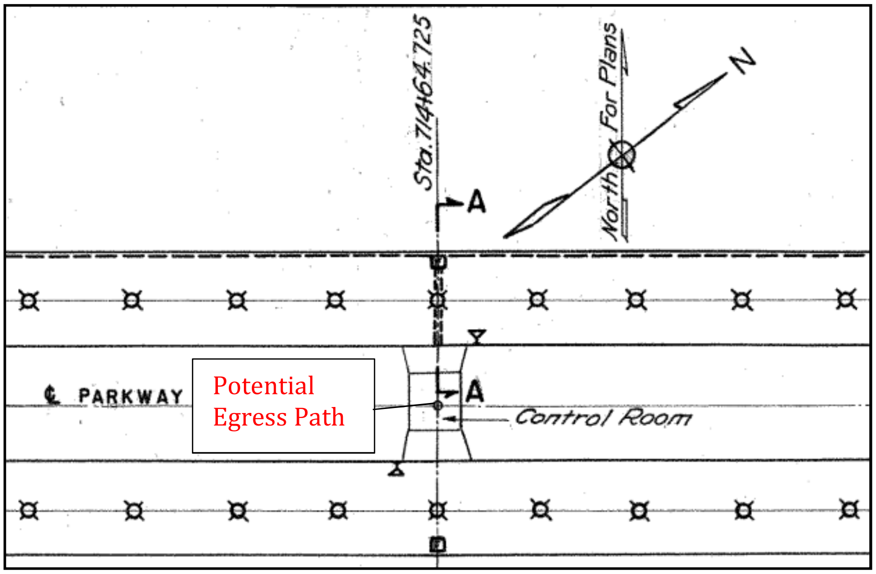


Figure 6-8
Potential Egress Path

However, it would not be safe for occupants to egress into the other tunnel barrel where traffic is moving at full speed. Under evacuation protocol, it will be necessary to stop traffic in both barrels to ensure occupancy safety.

6.5.6 Emergency Signage and Markings

Recommended emergency signage and markings are depicted on the attached graphic "Heroes Tunnel Emergency Signs and Markings" in accordance with NCHRP Web-Only Document 216, *Proposed Guidelines for Emergency Exit Signs and Marking Systems for Highway Tunnels* guidelines.

Sign and marking types would be selected to optimize visibility during the design of upgraded ventilation and safety features.

6.5.7 Upstream Warning Devices

As described previously, MUTCD expressway guidance for Advance Warning Area Section 6C.04 recommends that upstream warning devices should be located a ½ mile or more in advance of the tunnel or the temporary traffic control zone. Upstream warning devices may also be placed in advance of alternate routes to better inform drivers.

A system of permanent DMS installations at critical locations as part of an Incident Management System would provide the most responsive measure to control traffic along Route 15. DMS messages along Route 15 indicating a stopped condition and a description of the event within the tunnel will improve driver responsiveness to slowing and stopped conditions and allow opportunities to exit the highway and travel on local roads. By including regional installations at key interchanges such as Route 15 at the Milford Connector, I-95 at the Milford Connector, and I-91 at Route 15, drivers may choose alternate regional routes to circumvent the temporary traffic control zone.

6.6 Electrical Systems

This section serves as a summary of the electrical information presented in Section 3, 4, and 5.

CDM Smith conducted an electrical review of the Heroes Tunnel through existing plans, past inspection reports, and a site visit. There are electrical code non-compliances and equipment is beyond its useful life.

NFPA 502 lists several requirements for normal and emergency power systems within road tunnels. The existing power distribution system does not comply with NFPA 502, and the automatic transfer switch is potentially not functional. In addition, the conduit system at the tunnel shows signs of deterioration, including separation, cracking, and corrosion. Use of exposed PVC conduit within the tunnel is a life safety hazard and it should be replaced with metallic conduit.

An entirely new electrical system is recommended; the replacement includes upgraded electrical utility services, new distribution equipment, conduit, and wiring. Additional redundancy is recommended through the use of two utility services (supplying two automatic transfer switches) during normal operating conditions and installation of an emergency generator which will operate during power outages. Emergency loads will be powered from an emergency motor control center that has main-tie-main configuration for operational flexibility. It is recommended that critical loads, including lighting, control, and communications equipment, be further backed up by an uninterruptible power supply.

The lighting systems within the barrels are in poor condition and full replacement is recommended. Installation of ceiling centerline mounted LED lighting systems is recommended. During the day, light levels shall be high near the entry point of each tunnel to allow for eye adaptation and shall be incrementally reduced further into each tunnel. Nighttime luminance shall be constant throughout each barrel. It is recommended that a lighting control system be installed so that fixtures can be dimmed as required and scene setting can be programmed and operated both locally and remotely. During the day, it is recommended for the light output of the system to be controlled by a luminance photometer installed near the approach of each barrel.

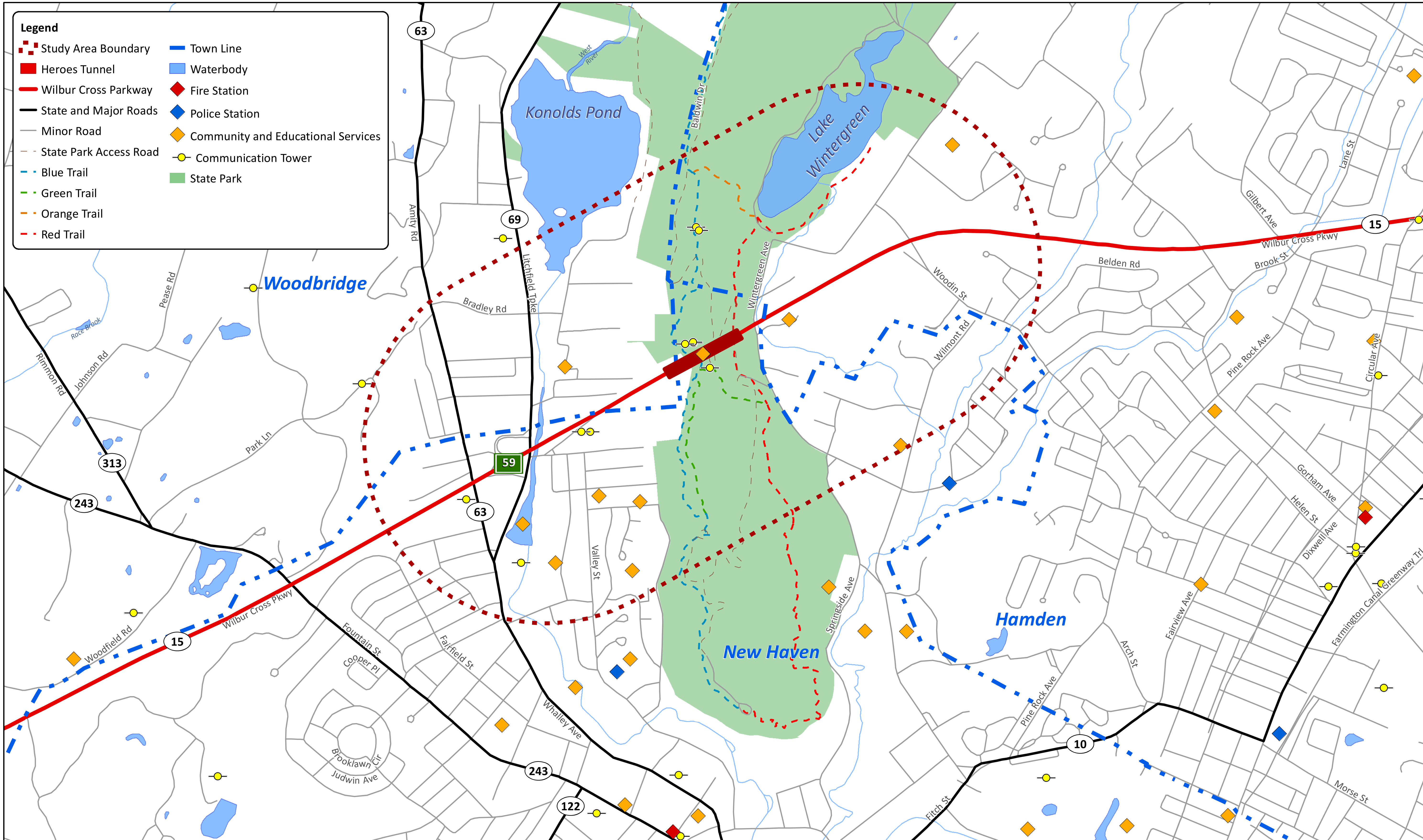
No egress or emergency lights exist at the tunnel. It is recommended that internally illuminated egress signs be located at each point of egress and throughout the tunnel.

No gas or fire alarm systems exist in the tunnel. It is recommended for manual fire alarm pull boxes to be installed per code requirements. Spot-type heat detectors are recommended. Carbon monoxide probes and analyzers are recommended to be installed.

It is recommended that all electrical distribution, control, and networking equipment be placed within a climate-controlled building.

6.7 Emergency Response Plan

Going forward, coordinators and participating agencies will be required to have an emergency response plan. This includes the fire departments in Woodbridge, Hamden, and New Haven. As the elements and improvements recommended in this study are developed the planning can commence between participating agencies. CDM Smith can provide the initial liaison service and the initial development of the emergency response plan. Figure 6-9 is provided to show the various services/agencies and local fire and police stations in the proximity of the Heroes Tunnel.



Data Sources:

- Connecticut Department of Energy and Environmental Protection
- South Central Regional Council of Governments

Date: June 2019

Community, Educational, Public Safety, and Emergency Response Services

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Feet

Heroes Tunnel Project

FIGURE 6-9