Tunnel Systems Report for the Freeway Tunnel Alternative

SR 710 North Study

Los Angeles County, California

Prepared for

Metro

Los Angeles County
Metropolitan Transportation Authority

September 5, 2014

This page intentionally left blank.

Executive Summary

This report summarizes the design considerations and analysis of electrical, ventilation and communication systems for the SR 710 North Study Freeway Alternative for Caltrans and LA Metro. Certain memoranda and studies performed as part of the CH2M HILL SR 710 North Study are included in the appendices. The electrical, ventilation and communication systems design considerations for Light Rail Transit are incorporated in the advanced conceptual engineering report for that alternative.

While urban road tunnels provide traffic solutions with a limited use of real estate, the underground environment requires special attention and design for ensuring the health and safety of motorists. In general, the systems installed for a roadway tunnel provide for convenient and safe operation of the tunnel environment and especially for fire protection.

Some of the technical aspects of the analysis can be highly technical, but these details are contained in the appendices. The body of this report provides a conceptual description of the purpose and function of these systems for the general reader.

A variety of mechanical, electrical, electronic equipment, and software systems are either required or recommended for the tunnel environment. These systems were developed in cooperation and coordination with Caltrans and LA Metro in accordance with recognized codes and standards. The following major systems and functionality are detailed in this report:

- Voice Communications Systems include the telephone and radio communications necessary for motorists and maintenance workers to converse for emergency and other purposes. A public address system provides the means to broadcast emergency to motorists as needed. An AM/FM radio rebroadcast maintains normal radio programming but also supports emergency message functions.
- Data Transmission and Control Systems provide the essential communication networks that transmit data and voice traffic for the other systems. The Operations Control Centers at both portal are centralized locations for monitoring and control.
- Traffic Detection and Control Systems monitor traffic volumes and incidents, and allow for control of traffic especially in emergency situations.
- Security Systems detect persons in the pedestrian areas of the tunnel and provide access control for secure areas of the tunnel facilities.
- Fire Detection Systems provide early and positive detection of fires in the tunnel. Early detection is ensured with multiple means of detection including heat, smoke, and flame.
- Tunnel Environmental Monitoring monitors tunnel air quality for the normal pollutants from motor vehicles. Air visibility and air velocity are also monitored. The ventilation system responds to maintain air quality, visibility, and velocity at safe limits as necessary.
- Electrical Systems provide the necessary power for all other systems. Emergency power is provided by uninterruptible power supplies and emergency generators.
- Lighting Systems provide safe lighting for the roadway and throughout the facilities. The lighting adjusts automatically to allow safe transitions from the varying outside brightness to the interior tunnel lighting.
- Fixed Fire Fighting Systems provide the means for quickly using water and/or foam to extinguish a fire in the tunnel. A deluge system allows water and/or foam to be applied to sections of the tunnel on vehicle fires. Standpipes and hoses and fire extinguishers provide the means to manually attack a fire. Professional fire fighters will be co-located at the portals for quick response to incidents.

- The Tunnel Ventilation System maintains the air quality and velocity during normal operation. During a fire emergency, the ventilation system maintains the tenability of the tunnel environment to allow for the safe evacuation of motorists and facilitate fire-fighting operations.

Figures

Tables

This page intentionally left blank.

List of Preparers

The following individuals have participated in the preparation of the SR 710 Systems Final Report, or have completed quality review, or both.

Contributing Authors:

Bernhard Hoepperger
Mechanical Engineer

Reinhard Gertl
Ventilation Engineer

Thomas Klaffenboeck
Mechanical Engineer

Alireza Haghighi, P.E.
Electrical Engineer

Christian Plattner
Mechanical Engineer

Hubert Heis
Senior Electrical Engineer

Bernhard Kohl, Dipl.-Ing.
Tunnel Safety Engineer

Thomas Marcher, PhD, Dipl.-Ing.
Discipline Lead Seismic Engineering

Bernhard Parth
Electrical Engineer

Johannes Pyka
Dispersion Expert

David Reitmeir
Mechanical Engineer

Benjamin Riedl
Electrical Engineer

Alexander Rudolf, PhD
Discipline Lead Tunnel Ventilation

Erich Saurer, Dipl. Bau-Ing., Dr. sc. ETH
Senior Seismic Engineer

Klaus Schmid
Civil Engineer

Franz Starjakob, Dipl.-Ing.
Senior Civil Engineer

Daniel Stix
Mechanical Engineer

Momchil Venkov, M.Sc.
Senior Electrical Engineer

Sherry Harris
Systems Engineer

Hans Haring, DP, Dipl.-Ing., MBA
Discipline Lead Tunnel Systems

Mohammad Ghaderi, PhD
Mechanical Engineer

Marc Knickerbocker, P.E.
Tunnel Ventilation

Reviewed by:

Conrad W. Felice, Ph.D., P.E. P.Eng, D.GE.
James A Morrison, P.E

This page intentionally left blank.

Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
bgs	Below Ground Surface
BRT	Bus Rapid Transit
Caltrans	California Department of Transportation
CE	Conceptual Engineering
CEE	Construction Evaluation Earthquake
CFD	Computational Fluid Dynamic
CNG	Compressed Natural Gas
CO	Carbon Monoxide
DCM	Design Criteria Memorandum
DSH	Design Seismic Hazards
DSHA	Deterministic Seismic Hazard Approach
EMFAC	EMission FActors for California database
EPA	US Environmental Protection Agency
FDS	Fire Dynamics Simulator software program
FEE	Functional Evaluation Earthquake
FFFS	Fixed Fire Fighting System
FLS	Fire/Life Safety
ft	Feet
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
in.wg	Inches Water Gauge (inches of water)
K_0	At-rest lateral earth pressure coefficient
km	Kilometer
kV	Kilovolt
LA	Los Angeles
LAFD	Los Angeles Fire Department
LAPD	Los Angeles Police Department
LGV	Light Goods Vehicle
LRFD	Load and Resistance Factor Design
LRT	Light Rails Transit
m	Meter
MCE	Maximum Credible Earthquake

MDE	Maximum Design Earthquake
Metro	Los Angeles County Metropolitan Transportation Authority
moz	Micro Ounce
NCHRP	National Cooperative Highway Research Program
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
noz	Nano Ounce
NOx	Nitrogen oxide
OCC	Operations Control Center (room contained within OMC)
ODE	Operating Design Earthquake
OMC	Operations and Maintenance Control buildings
oz	Ounce
PBL	Planetary Boundary Layer
PGA	Peak Ground Acceleration
PID	Piping and Instrumentation Diagram
PM	Particulate Matter
PP	Micro-polypropylene (PP) Fibers
PSHA	Probabilistic Seismic Hazard Approach
SCADA	Supervisory Control and Data Acquisition
SEE	Safety Evaluation Earthquake
SR 710 tunnel	any State Route 710 road tunnel alternative under consideration
TBM	Tunnel Boring Machine
TM	Technical Memorandum
TSM/TDM	Transportation System Management/Transportation Demand Management
z_o	Surface Roughness Height

1 Introduction

In 2011, LA Metro contracted with the CH2M HILL team to conduct an environmental study to identify project alternatives to address the traffic congestion within and beyond the SR 710 corridor. LA Metro is the contracting agency for the environmental study, and Caltrans is the lead agency assigned authority to ensure the study is conducted in compliance with the National Environmental Policy Act (NEPA) and the California Environmental Quality Act (CEQA).

The SR 710 transportation corridor was originally envisioned to extend north from the City of Long Beach to the I-210/SR 134 and SR 710 interchange in the City of Pasadena. The segment between I-10 and the I-210/SR 134 and SR 710 interchange is the only uncompleted section.

For decades, planning efforts to improve mobility and relieve congestion on local arterials and nearby freeways were limited to a surface extension of the SR 710 freeway. The California Department of Transportation (Caltrans) and Los Angeles County Metropolitan Transportation Authority (LA Metro) are now considering a range of alternatives to address the problem.

There are five alternatives being considered in the SR 710 North Study.

- No Build
- Transportation System Management/Transportation Demand Management (TSM/TDM)
- Bus Rapid Transit (BRT)
- Light Rail Transit (LRT)
- Freeway Tunnel

The scope of this report is focused on the Freeway Tunnel alternative. Systems recommendations for the other alternatives are addressed in separate reports.

The freeway tunnel alternative is feasible due to advances in tunnel boring machine technology over the last 25 years, allowing greatly increased tunnel diameters. For this alternative, LA Metro and Caltrans are considering dual-bore tunnels with 17.8 m (58.5 feet) diameters and approximately 7.9 km (4.9 mile) long between East Los Angeles and Pasadena. If this alternative is selected, it would rank as one of the largest urban mega-tunnels in the world.

The systems design considerations for this mega-tunnel are the focus of this paper.

1.1 Objective and Scope

Systems are essential for the operation, maintenance and safety of roadway tunnels. This report summarizes the preliminary design considerations and analysis for the freeway tunnel alternatives related to the systems requirements. The scope of this design phase was to establish the feasibility and technical requirements for key systems especially and including ventilation, fire/life safety, communications and control. This report is a compilation of memoranda and studies performed as part of the CH2M HILL SR 710 North Study and those memoranda are reproduced and referenced as appendices herein. This report serves as the comprehensive summary of that work product and supersedes all earlier reports and memoranda.

1.2 Purpose and Need of Systems

“Systems” generally refers to the mechanical, electrical, electronic and software installations in a facility. For road tunnels Systems provides essential operational, maintenance, environmental and life/safety functions. Major systems functions include ventilation, fire suppression and detection, electrical power, environmental monitoring, equipment monitoring and control (SCADA), traffic control, as well as voice and data communications. Systems equipment is installed throughout the tunnel and portal facilities. The many systems in a road tunnel allow for the operations, maintenance and management of complex processes to ensure public safety.

> Fire Protection Handbook, Section 21, Chapter 11: *A road tunnel is defined as any enclosed facility through which road vehicles (cars, vans, buses, and trucks) travel. These vehicles are typically powered by internal combustion engines using traditional fuels such as gasoline and diesel.*
>
> *Fire protection for road tunnels requires a unique application of common fire protection, fire fighting, and fire suppression systems and techniques. The fire load in a tunnel is continuously changing and is basically unpredictable. The potential always exists, however, for fires to occur that are of significant scale in comparison to most commercial structures. Also, unlike commercial or industrial buildings and facilities, road tunnels do not offer any compartmentalization, making evacuation and rescue far more difficult.*

This report summarizes the systems elements designed for the SR 710 freeway tunnel alternative that are necessary for effective road tunnel operations and fire/life safety.

1.3 Freeway Tunnel Alternative Location

The SR 710 North Study area is situated in the east/northeast Los Angeles and west San Gabriel Valley area.

As shown in Figure 1, the area is approximately 260 km^2 (100 mi^2) and generally bounded by:

- I-210 on the north
- I-605 on the east
- I-10 on the south
- I-5 /SR-2 on the west

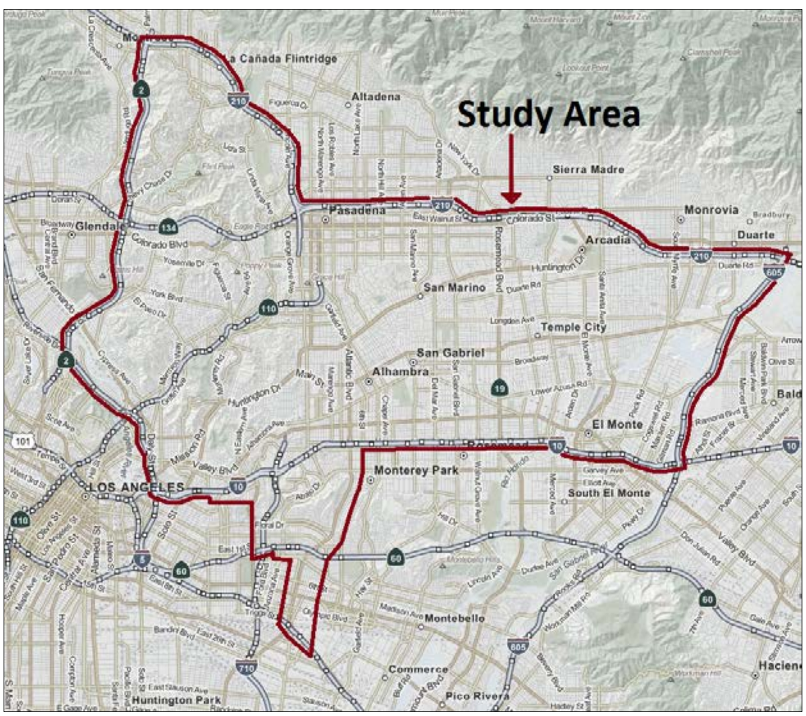


Figure 1: SR 710 North Study Area

As shown in Figure 2, the Freeway Tunnel Alternative starts at the existing southern stub of SR 710 in Alhambra, just north of Interstate (I)-10, and connects to the existing northern stub of SR 710, south of the I-210/SR 134 interchange in Pasadena.

The Freeway Tunnel Alternative includes the same improvements proposed for the TSM/TDM Alternative with the exception of Improvements T-1 and T-3.

The bored tunnels would be located about 36.6 – 85.3 m (120 - 280 feet) below the surface.

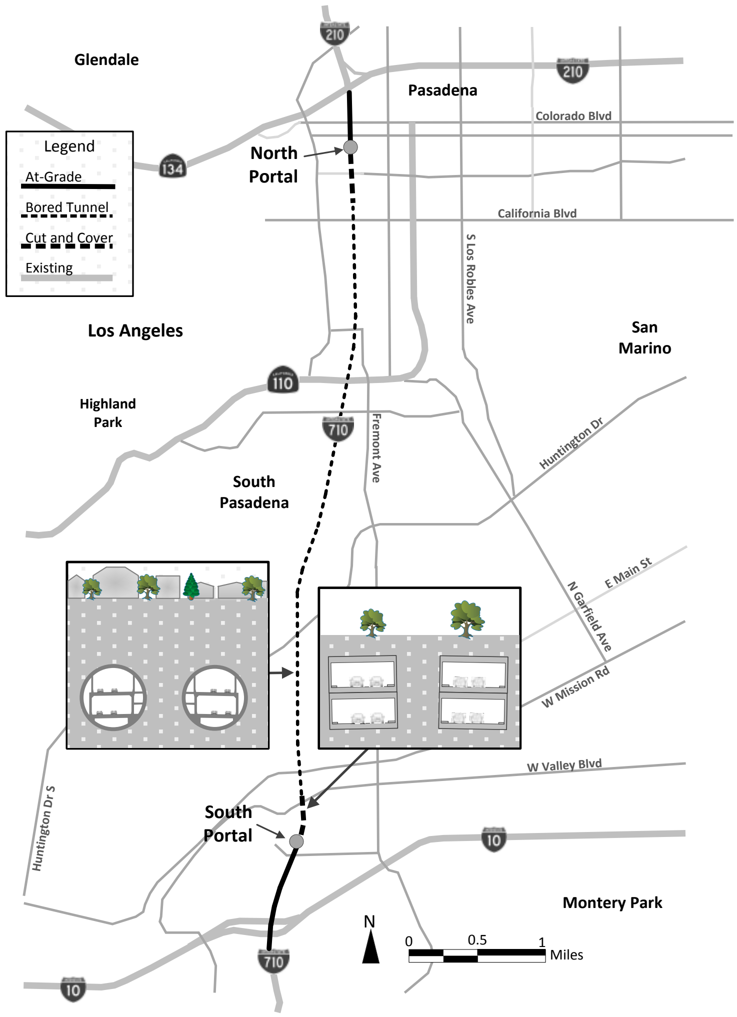


Figure 2: Freeway Tunnel Alternative Alignment

1.4 Freeway Tunnel Design Variations: Dual Bore and Single Bore

The Freeway Tunnel Alternative has two design variations: a dual-bore tunnel and a single-bore tunnel. The dual-bore design variation includes two tunnels that independently convey northbound and southbound vehicles. The single-bore design variation includes one tunnel that carries both northbound and southbound vehicles. Figure 3 illustrates the dual-bore and single-bore tunnel design variations.

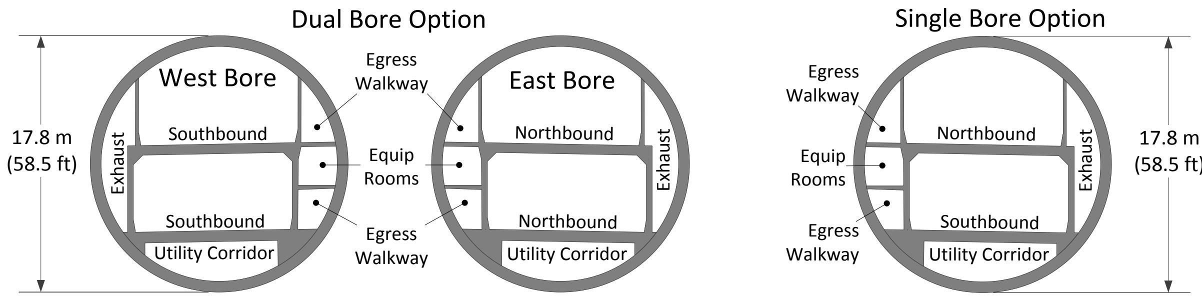


Figure 3: Dual Bore and Single Bore Tunnel Design Variations

The bored tunnels would be located about 36.6 – 85.3 m (120 – 280 feet) below the surface.

Each of these design variations is summarized below.

- Dual-Bore Tunnel: The dual-bore tunnel variation is approximately 6.3 miles long, with 4.2 miles of bored tunnel, 0.7 mile of cut-and-cover tunnel, and 1.4 miles of at-grade segments. This tunnel variation has two side-by-side tunnels (one northbound and one southbound), with two levels and two lanes of unidirectional traffic and shoulder per level for a total of four lanes per tunnel. Each bored tunnel has an outside diameter of approximately 60 feet; and the crown of each tunnel is approximately 160 feet below ground surface along most of the tunnel. Vehicle cross-passages between the bores for emergency use would be provided, nominally spaced every 914 m.
- Short segments of cut-and-cover tunnels are located at the southern and northern termini to provide access from the portals to the bored tunnels. The portal at the southern terminus is to be located south of Valley Boulevard. The portal at the northern terminus is to be located north of Del Mar Boulevard. No intermediate interchanges are planned for the tunnel.
- Single-Bore Tunnel: The single-bore tunnel design variation is also approximately 6.3 miles long, with 4.2 miles of bored tunnel, 0.7 mile of cut-and-cover tunnel, and 1.4 miles of at-grade segments. This tunnel variation consists of a single, two-level, bored tunnel with two lanes on each level in each direction. The single-bored tunnel also has an outside diameter of approximately 60 feet; and the crown of the tunnel is located approximately 160 feet below ground surface along most of the tunnel. The single-bore tunnel would be in the same location as the northbound tunnel in the dual-bore tunnel design variation.

Both design variations include the following tunnel support systems.

- Ventilation system
  - Exhaust fans at each portal
  - Single exhaust duct along the entire length of the tunnel
  - Jet fans within the traffic area of the tunnel
  - Air scrubbers at the portals
- Evacuation
  - Protected egress pedestrian walkways
- Fire detection systems
  - Linear heat detection
  - Optical detectors
  - Video image detection
- Fire suppression
  - Deluge foam water system (fixed fire fighting system)
  - Standpipe and hose system
  - Fire extinguishers
- Communications
  - Variable message signs

  - Emergency telephones
  - Public safety radio
  - Wireless broadband network
- Operations and Maintenance Center (OMC) buildings at both the portals
  - 24-hour surveillance
  - Co-located first responders and fire fighting vehicles

In addition to the systems described above, vehicle cross-passages are provided as an added measure for dual-bore tunnel option. Also, both tunnel design variations include roadway improvements outside the north and south portal areas.

There are no operational restrictions for the tunnel, with the exception of vehicles carrying flammable or hazardous materials.

1.5 Primary Guidelines and Standards

NFPA specifies the following for tunnel design:

> Fire Protection Handbook, Section 21, Chapter 11: *Guidelines and standards for road tunnel fire protection have been published worldwide by both international organizations and individual countries. Both the National Fire Protection Association (NFPA) and the World Road Association (PIARC) publish standards and guidelines on road tunnel fire protection.*
>
> *The definitive standard for road tunnels is NFPA 502. Elements of several other NFPA codes and standards may be applied to fire protection systems within road tunnels; these codes and standards are appropriately referenced in NFPA 502.*

The systems design presented in this report complies with NFPA 502, and other NFPA standards that it references. A comprehensive list of guidelines and standard that may apply to the future final design are provided in Appendix A, Guidelines and Standards.

This page intentionally left blank.

2. Operations Maintenance and Control Building

The operation-maintenance-control (OMC) building is part of the ventilation/control building near the south portal of the tunnel. The required rooms for the OMC building are separated into two levels (first floor and second floor), and two buildings (left and right building of the ventilation and control building) and cover an area of approximately 22,500 ft².

The HVAC system of the OMC building provides air conditioning (cooling and heating) and has separate control units in each zone (left/right building and 1st/2nd floor). Additional building services, such as water supply and waste water treatment, must be coordinated with the local municipality and will be designed in the second phase of the project (preliminary design).

2.1 Functional Zones of the OMC Building

There are six functional zones within the OMC building.

Table 1: Functional Zones within the Operations and Maintenance Building

Functional Zone	Functionality of the Zone
Operational zone	Station control room, offices, meeting rooms, event/meeting room
Crew workshops	Workshops for electrical and mechanical crews
General rooms	Restrooms, washrooms, break room
Equipment rooms	Switchgear rooms, control equipment rooms, generator rooms, HVAC room
Storage rooms	Archive rooms, mechanical/electrical spare part rooms
Garage	Garage for approximately three maintenance vehicles

The final room configuration will be defined during the next project design phase.

2.1.1 Offices

The design considers seven office rooms for the operation and maintenance staff. The installed equipment in each office room depends on the staff using the room and will be coordinated with the requirements of the overall operation and control tasks of this OMC building.

2.1.2 Maintenance Areas

There are several areas for maintenance and repair works considered. In addition, a garage room for maintenance vehicles is to be located in the OMC building.

2.2 Operation Requirements

The following describes the operation requirements for the tunnel alternatives.

> Fire Protection Handbook, Section 21, Chapter 11: *An effective road tunnel fire protection system program must contain the following elements: fire identification, verification and detection, emergency communications, smoke management, fire suppression, emergency response planning, evacuation and rescue, and traffic control.*

For specific recommendations, see Appendix B.

2.2.1 Operation and Control Center (OCC) Room

The operation and control center is to be used only for the operation of the F-7 freeway tunnel. Additional control functions are not considered (overall control responsibility) for other freeway tunnel alternatives. The operation and control room is to be located on the second floor of the OMC building

2.2.2 Connection to Overall Traffic Control System

The traffic control system of the tunnel must be connected directly to the overall regional traffic control system; specifics will be addressed as part of the final design.

In this case the control system of the tunnel has first priority in case of any emergency and forwards necessary information on a second priority level to the overall traffic control system.

3. Electrical and Communications Systems

This section describes the electrical and electronic systems necessary for ensuring the health and safety of motorists and personnel for the freeway tunnel alternatives. There are two tunnel structure design variations under consideration: a Single Bore Tunnel and a Dual Bore Tunnel. From the perspective of the tunnel operation and safety systems design, there is no difference between these design variations except in the number of system components. All information in this report applies equally to both design variations.

The recommended systems and equipment are broadly categorized as follows:

- Voice Communications Systems
- Data Transmission and Control Systems
- Traffic Detection and Control Systems
- Security Systems
- Fire Detection Systems
- Tunnel Environmental Monitoring
- Electrical Systems
- Lighting Systems

3.1 Voice Communications Systems

Communication Systems enable the communication for the tunnel motorists and for tunnel operators as well as for the emergency services. It functions to enable people to communicate in case of emergency and to instruct and guide them to exit dangerous areas. It consists of the telephone system for emergency and maintenance purposes, the radio system for radio frequency and voice communication inside the tunnel and of a public address system (PA) for announcements to tunnel drivers in case of emergency.

3.1.1 Telephone System

The Telephone System is installed for the voice communication between several locations inside the tunnel and the Operations Control Center. The telephone system is to be connected to the Public Switched Telephone Network (PSTN) and to the SCADA system. It mainly consists of the central components (like IP phone controller) at the portal buildings and telephones for the following purposes:

- Maintenance Telephones
- Emergency Telephones

Emergency telephones provide voice communication between persons in the tunnel area and the operator at the Operations Control Center. The tunnel operator at the OMC is alerted whenever an Emergency Telephone is taken off-hook. The operator can then determine the appropriate response to be initiated.

The Emergency Telephone System is visualized on an active screen at the Operations Control Center and all received signals (for example, push-button activation and position switches) are detected and addressed separately. The off-hook emergency telephones are highlighted on the active screen and the view of the nearest CCTV camera is automatically shown. The Emergency telephone system will be configured to automatically report any problem with the phone or phone line.

Emergency telephones must be installed inside the tunnel and inside the emergency walkways. They are placed at every communication room and every emergency exit. The spacing between the call boxes is recommended to be about 230 feet.

Maintenance telephones with dialing capability enable the operation and maintenance staff to communicate through an internal IP-based telephone network which is independent of the emergency telephone network. The maintenance telephones are installed in communication rooms, at the utility corridor level, and in various areas and rooms in the portal buildings.

3.1.2 Radio System

The Radio System is installed for continuous radio frequency communications in the tunnels and portal buildings to enable voice communications between the Operations Control Center, maintenance workers, as well as external agencies. It provides the primary means for voice communication in the tunnel areas during normal operation and in case of emergency.

It functions to guarantee uninterrupted radio communication inside the tunnel, at the tunnel portals and inside the walkways. The tunnel radio system allows for emergency communication, especially for the following groups: police, sheriff, fire brigade, ambulance services and tunnel operators. A two-way radio system is required for communication of fire fighters with the fire command center.

It mainly consists of the radio terminals, antennas, electro-optical converters, radiating cables (also known as leaky feeder cables) and ancillary cabling.

The terminal for the radio system is to be located in the portal buildings. The terminal receives the radio signal from the antennas and pass it on to the amplifiers by fiber optic cables. There are three antennas; the 800 MHz antenna is to be used for the public safety service, and the others for AM and FM signals. Cross-band couplers transfer signals from the override generator to the amplifiers and electrical-to-optical converters. Electrical-to-optical (E/O) converters transmit the electrical signals to the communications rooms inside the tunnel through fiber optics. In these rooms, there are optical-to-electrical (O/E) converters to generate electrical signals out of the optical signals. Two AM radiator cables and one FM leaky coaxial cable are connected to the amplifiers to supply each tunnel sector with the radio signal. The two AM and the FM leaky coaxial cables are installed on the ceiling of the tunnel tube. To guarantee a proper AM signal, a counterpoise cable must be mounted in the tunnel. The tunnel is divided into sections to reduce the maximum failure length. The typical length of these sections is about 3,000 feet. Leaky cabling is to be installed also inside the emergency walkways to supply this area with a two-way radio system.

At the portal buildings and inside the tunnel, space and electrical power is provided to install mobile phone antennas and equipment to provide mobile phone coverage. Tunnel drivers can make an emergency call with a cell phone inside the tunnel.

The exact definition about the required channels, talk groups, and frequencies will be coordinated with the local authorities for the detailed design. At the Operations Control Center, the tunnel operator can speak over and listen on all radio channels. For traffic announcements on AM or FM radio channels, ad hoc and prepared announcements are possible.

3.1.3 AM/FM Radio Rebroadcast System

This system allows the tunnel operator to broadcast announcements to tunnel motorists through their car radio. For example, in case of a fire, a typical announcement might be “Please leave your car and walk to the nearest emergency exit”. Local radio stations are connected to the system, so that motorists can continue listening to radio programming while in the tunnel.

3.1.4 Public Address (PA) System

The PA system is installed to perform public announcements and enables communications from tunnel operator to tunnel motorists, such as providing verbal direction to tunnel motorists in case of emergency. The components of this system include controllers, amplifiers, conventional loudspeakers, and pressure zone horn speakers.

The system is to be as a synchronized, longitudinal acoustics system with pressure-zone horn speakers installed at regular distances on the tunnel ceilings. Conventional loudspeakers are mounted for public announcements inside the emergency walkways. The spacing between the loudspeakers is recommended to be about 200 feet. The system controller for configuration, monitoring, and controlling the PA system will be installed at the Operations Control Center. The amplifiers are to be installed in the communications rooms inside the tunnel and in the Portal buildings.

Announcements can be given by the tunnel operator through the microphone at a workstation where single loudspeakers can be switched separately. It is also possible to play back recorded messages or give announcements using the tunnel radio system. The PA system is monitored by SCADA.

3.2 Data Transmission and Control Systems

3.2.1 Operations Control Center (OCC)

The tunnel can be managed from either of two Operations Control Centers that are within the OMC, located at the portal buildings. In addition to this redundant configuration at the tunnel, the design may include the capability for all OCC functions to be implemented from a remote facility, such as a Caltrans regional traffic management center.

The OCC functions to monitor and control the entire tunnel as well as the approach roadways. The layout consists of a control room with a video wall, several operator consoles, and a supervisor console.

In addition to the control room itself, other supporting rooms are recommended such as a computer equipment room, crisis management room, visitor gallery, and provisions for 24/7 staffing.

For specific recommendations about staffing, see Appendix B.

Figure 4: Typical Operations Control Center

3.2.2 Supervisory Control and Data Acquisition (SCADA) System

The SCADA system provides all monitoring and control for all systems and equipment within the tunnels, portals, and portal buildings.

The SCADA system must be designed to automatically control tunnel systems with minimal operator intervention required. The communication foundation for the SCADA system is be a redundant, fail-safe Ethernet network with remote I/O units monitoring status and alarms. Supervisory control capability is provided from either Operations Control Center.

SCADA systems components are distributed throughout the tunnel with major concentrations at the communications rooms, portal buildings, and in intermediate cabinets.

At the operation building and the electrical substation, servers are connected to switches. These switches are connected to switches in every low-voltage distribution room at the vehicle cross passages by fiber optic cables.

3.2.3 Communications Network

The communication network is installed for supervising systems and control systems. The bandwidth has to be determined when the amount of equipment in the tunnel is defined. It consists of cable transmission systems (CTS) and the tunnel wireless broadband network.

3.2.3.1 Cable Transmission System (CTS)

The CTS consists of the inside and outside plant cabling infrastructure and network equipment providing Ethernet in the portal buildings and tunnel areas. The CTS transports all network data, voice, and video traffic within the tunnel to the Operations Control Centers. At the portal buildings and the communications rooms, servers are connected to routers. These routers are connected to switches in every communications room near the cross passages by fiber optics. The fiber optics is built as a redundant ring laid through different decks and tubes, so that cable interruption at any point doesn't cause a communication blackout.

Cabinets for data and power supply connection of the remote tunnel equipment are placed in the emergency walkways every 305 m (1000 feet) between the communications rooms. The cables are led to the tunnel equipment through cable ducts set in the tunnel lining.

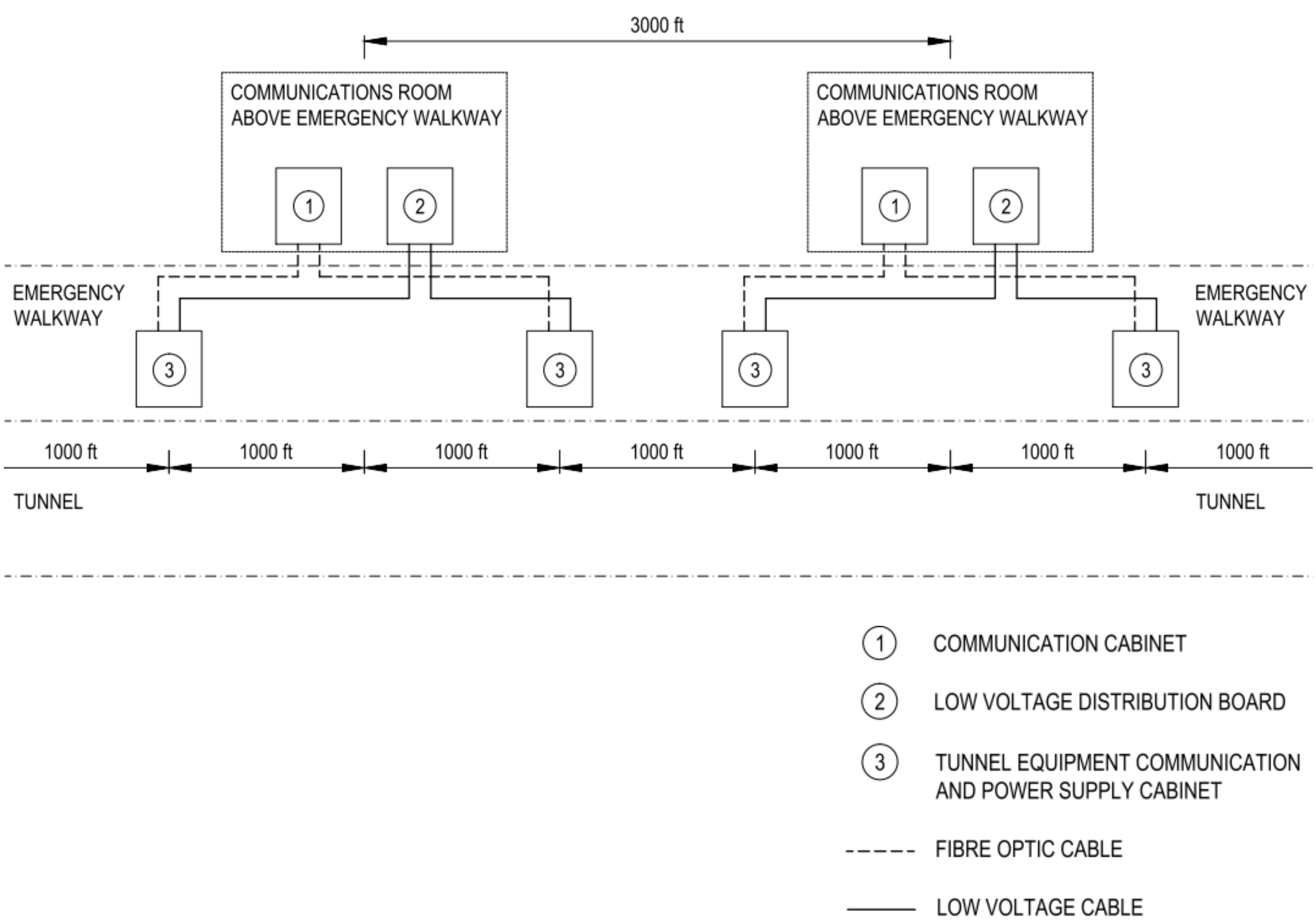


Figure 5: Tunnel Equipment Communication and Power Supply Cabinets

3.2.3.2 Tunnel Wireless Broadband Network

Until recently, first responders at the scene were limited to voice communications with the incident command center. With the advent of licensing in the 4.9 GHz spectrum for the exclusive use of public safety agencies, the design includes a broadband communications network in the tunnels.

Wireless transmission devices are to be installed on the tunnel ceiling to provide broadband network within the tunnel and along the roadway. This wireless network is dedicated to safety and security functions and allows greater situational awareness for first responders with live video transmitted to and from emergency vehicles equipped with wireless capability. In the future this network could also provide the communications infrastructure necessary for remotely controlled robotic vehicles, such as firefighting drones.

3.2.3.3 Network Management System

The network management system (NMS) assists technicians with maintenance tasks of the communications network. An NMS is typically a combination of hardware and software that provides capability for configuration, management and monitoring of the network as well as networked devices such as [list devices].

Maintenance tasks facilitated by the NMS include:

- network device discovery: identifying devices present on the network
- network device monitoring: monitoring the health of network components
- network performance analysis: tracking of network performance and utilization metrics
- notifications: configurable alerts to notify network technicians of problems or failures

3.3 Traffic Detection and Control Systems

Traffic Detection and Control systems detect, monitor, and control traffic within the tunnels, at the portals, and on the approach roadways. Detection is implemented through video and acoustic analytics to provide real-time volumes and incident detection. Detected time-stamped historical traffic data is collected, processed, and archived for assist traffic management and planning. Traffic control allows the tunnel operator to manage lane or tunnel closures through activation of signs and gates.

Traffic detection and control systems for the tunnel must be integrated with the Caltrans regional traffic management systems.

3.3.1 Traffic Control System

Traffic control provides motorists with roadway conditions and alerts. Dynamic speed limits and lane use signs allow the tunnel operator to manage traffic for various conditions and incidents. The tunnel operator can assess conditions through CCTV and respond to minimize dangerous and abnormal conditions. Elements of this system include a traffic stop system including tunnel closure signs and tunnel closure gates. Various traffic signs including variable message signs which can be activated with ad hoc or predefined messages.

3.3.1.1 Traffic Stop System

A traffic stop system is necessary to stop any traffic from entering the approach roadways to the tunnels in case of an emergency in the tunnel. The traffic stop system includes traffic signs within the tunnels as well as on the approach roadways. Tunnel closure gates are provided on the tunnel approach roadways.

3.3.1.2 Traffic Signs and Variable Message Signs

Different kinds of traffic signs provide for safety and informational purposes in the tunnels, at the portals, and on the approach roadways. Traffic signs support the procedures for regulating traffic during emergencies. As specified in NFPA 502, traffic must be managed to facilitate emergency responder access to the incident.

Variable message signs (VMS) are placed in the tunnels, at the tunnel portals, and on the approach roadways to control traffic within the tunnel, to clear traffic downstream of a fire site following the activation of a fire alarm within the tunnel, and to inform the motorists about accidents or provide any other necessary information. In addition, the speed limit signs shall be located at the same locations as the VMS and traffic signals following the recommendations of NFPA 502 to ensure maximum visibility to motorists. VMS must be installed at a nonperpendicular angle, but designed to appear flat from the motorist's point of view, thus maximizing the apparent size of the sign.

In order to prevent entry of vehicles with explosive or flammable loads, a "No Explosives or Flammable Materials" sign must be located ahead of the tunnel entrance, where the driver can still detour to avoid entering the tunnel.

Emergency exit signs guide motorists inside the tunnel to the cross passages and the emergency walkway in the event of an emergency. These exit signs must be illuminated at least 54 lx and shall produce a minimum luminance of 8.6 cd/m². These exit signs and all safety signs must be connected to the emergency power supply system.

In addition to these safety signs, informal signs (for example, "Turn on Headlights" and "Tunnel") will be placed about 300 feet in advance of the tunnel portal.

All traffic signs must be installed according to the California Manual on Uniform Traffic Control Devices (California MUTCD) and NFPA 502.

3.3.2 Traffic Detection System

Various traffic detection devices for different purposes must be included. Detection loops measure traffic volumes. Overheight vehicles detection systems must be located outside the tunnels. When an overheight vehicle is detected, warning signs with flashing beacons, horns, and signs with strobes are activated.

Traffic detection systems interface with the SCADA system. Alarms are transmitted to the Operations Control Center for manual and/or automatic intervention.

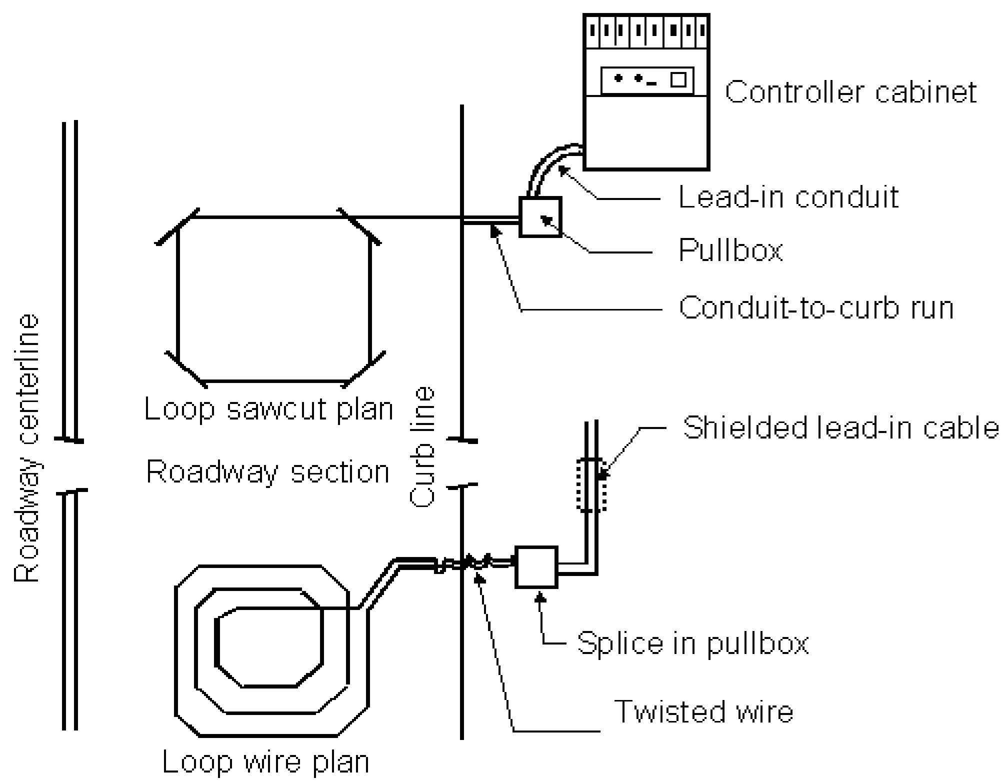


Figure 6: Inductive Loop Traffic Detection

3.3.3 CCTV System

The CCTV system with automatic video detection capability must be provided for general supervision of traffic conditions within the tunnel. Video detection can identify wrong-way driving, smoke, debris on the roadway, and other hazards. The detection system is linked to the fire alarm control panels (FACP) to trigger alarms in case of smoke detection inside the tunnel. In the emergency walkways, fixed view cameras are installed and mounted for monitoring pedestrian evacuation.

Color pan-tilt-zoom type (PTZ) cameras are mounted inside the tunnel near emergency exits and outside of the tunnel. For incident detection purposes, color, fixed-view cameras are mounted inside the tunnel at intervals of approximately 400. These cameras are used to supervise the traffic flow and are also used to identify wrong-way driving, smoke, obstacles on the road, and other hazards. All cameras include Digital Signal Processing (DSP) that can produce color images during bright conditions and high sensitivity monochrome images during dark conditions.

Video transmission from the cameras to the Operations Control Centers is full-motion color video transmitting at 30 images per second. Digital video recording capabilities must be provided for all CCTV cameras. A minimum of seven days of storage at the resolution and frame rate generated by the camera is required for each camera view.

Camera mounting height and location for each camera location must be designed to provide the needed coverage and field-of-view. Installation locations must also consider ease of maintenance and cleaning.

The CCTV system interfaces with the network router in the communications rooms inside the tunnel and with the main network routers in the portal buildings. If the cabling distance from the camera and network router is too long, range extenders can be used. Camera may also transmit on dedicated fiber optic cables.

3.3.4 Acoustic Tunnel Monitoring System

An acoustic tunnel monitoring system must be provided in the tunnel. Junction boxes are mounted on the tunnel wall at the CCTV locations. These boxes include integrated microphones mounted on the face to monitor tunnel sounds. The microphone signals are converted in the box to digital data signals and transmitted to centralized computer. This computer uses digital signal processing algorithms to detect anomalous sounds such as a vehicle collision, squealing tires or load spills. An alarm is then transmitted to the Operations Control Center for the tunnel operator to evaluate the situation. Video from the closest camera to the microphone where the anomalous sound is detected automatically opens on the operator’s screen or the video wall.

The analysis computer, where the software is installed, will be located at the south portal building. For post incident analysis, data storage for the tunnel audio must also be provided. The acoustic tunnel monitoring system interfaces with the SCADA system for alarm generation.

3.4 Security Systems: Intrusion Detection and Controlled Access

In addition to the CCTV system, an intrusion detection system detects door openings and pedestrian traffic in the egress walkways. Card key access control with intrusion detection must be provided in the communications rooms and the portal buildings. The access control system consists of card readers, position switches, request to exit detectors and electric strikes or latches connected to an access control panel. This system only allows access to sensitive locations (such as communications rooms or electrical rooms) to staff with an authorized card key. The tunnel operator receives intrusion alarms for any monitored or controlled door in the tunnel or portal facilities.

3.5 Fire Detection Systems

The fire alarm and detection system includes an addressable digital system with manual and automatic alarm initiation, automatic heat and smoke detectors, and signal transmission through signal line circuits dedicated to fire alarm services only.

> Fire Protection Handbook, Section 21, Chapter 11: *Heat detectors, flame detectors, and digital imaging systems (using CCTV) are the most applicable forms of automatic fire detection systems for road tunnels. The most prevalent type of detector used in road tunnels worldwide is the heat detector— more specifically the linear heat detector. CCTVs using digital imaging are a relatively new technology compared to linear heat detectors.*

3.5.1 Fire Detection Methods

Fire detection systems provide multiple independent methods to detect a fire and its location.

- Linear heat detection
- Optical detectors
- Video image detection (CCTV Analytics)

Most tunnels around the world have just one or two of these systems. These three systems provide high redundancy, which increases safety. A study was performed to predict the expected performance for each of the detection systems using data from existing road tunnels. Based on this real-world data, it is estimated that the combined detection systems will be capable of detecting 80% of fires within 30 seconds and 100% of fires within 65 seconds. Small fires are more challenging to detect because of the limited smoke and low temperature change within the first few minutes. Larger fires are detected within seconds.

Fire alarms can also be manually initiated by the tunnel operator based on CCTV observation or based on a call from an emergency phone or other voice channel.

The components of the fire alarm detection system consist of detection devices and systems, fire alarm control panels (FACP), and dedicated communication cabling. Fire alarms in the FACP automatically activate the fixed fire-fighting system and automatic ventilation controls in conjunction with tunnel operator commands. Operators will need to be cognizant of the effect of the deluge water on moving traffic. Ideally, traffic will be slowed or stopped before activation of the FFFS.

An FACP workstation computer is needed in the communications control rooms in the tunnel and at both of the Operations Control Centers. Fire alarms will be reported to the local fire department. Automatic smoke and heat detectors, manual fire alarm boxes, and horn/strobe alarms are installed in the Operations Control Center and in other rooms of the Portal buildings. Combination smoke/heat detectors are also installed in all equipment rooms inside the tunnel. Linear heat detectors must be installed on the tunnel ceilings. This system uses a heat-sensitive cable as an alarm element. Linear heat detection is capable of identifying a fire location within 50 feet or less. Due to the significant width of the tunnel decks, two cable lines per roadway deck may be required.

Fire alarm control panels (FACPs) must be installed in the Operations Control Centers and in the communications rooms to monitor alarms for the tunnel and facilities, including the linear heat detector system alarms. The FACUs are connected to each other in a network by fiber optic cables. The FACP also monitors the fire suppression system, including the building sprinklers and tunnel standpipe system.

On the tunnel roadway, emergency telephones are used in place of manual fire alarm boxes. When a motorist lifts the handset of an emergency telephone, the tunnel operator is alerted. If the motorist reports a fire, the tunnel operator can verify through CCTV and initiate an alarm.

3.5.2 Fire Extinguishers

Portable fire extinguishers must be located approximately at least every 300 feet in the tunnels. When the door to fire extinguisher cabinet is opened, a door switch is activated to trigger an alarm.

> *NFPA 502 7.9.1 requires portable fire extinguishers to be located in the tunnel roadway in wall cabinets at 300 foot (90 m) spacing. The size and type of portable extinguishers are defined as 2-A:20-B:C and 20 lb (9 kg) as defined in NFPA 10, Standard for Portable Fire Extinguishers.*

3.5.3 Positive Alarm Sequence

Multiple detection systems must be combined in a way that provides situational awareness clearly to the operators who make the fire response decisions. To prevent false alarms from triggering a response, the system is configured with a positive alarm sequence as prescribed by NFPA 72, 6.8.1.3. The operator is able to quickly confirm actual incidents and precise roadway location using the CCTV system. When an alarm occurs, the operator has a certain period of time to determine if it is a false alarm or not. If it is a false alarm, the operator can delay the response, until the alarm is cleared and reset. If the operator takes no action, the FFFS will be automatically activated.

3.6 Tunnel Environmental Monitoring

Various sensors and instrumentation systems provide continual monitoring of critical environmental conditions within the tunnels for health and safety. Signals from the sensor systems are used as inputs for automated control of the ventilation system. For example, the flow of outside air into the tunnel is increased by speeding up the exhaust fans. If environmental conditions are outside of prescribed limits, alarms are triggered through the SCADA system to alert tunnel operators to take appropriate action.

Multiple sensors on the roadway are connected to air quality/velocity control units in the communications rooms. The units are connected to the communications network for transmission of sensor analog data, discrete alarms, and diagnostic functions to the SCADA system.

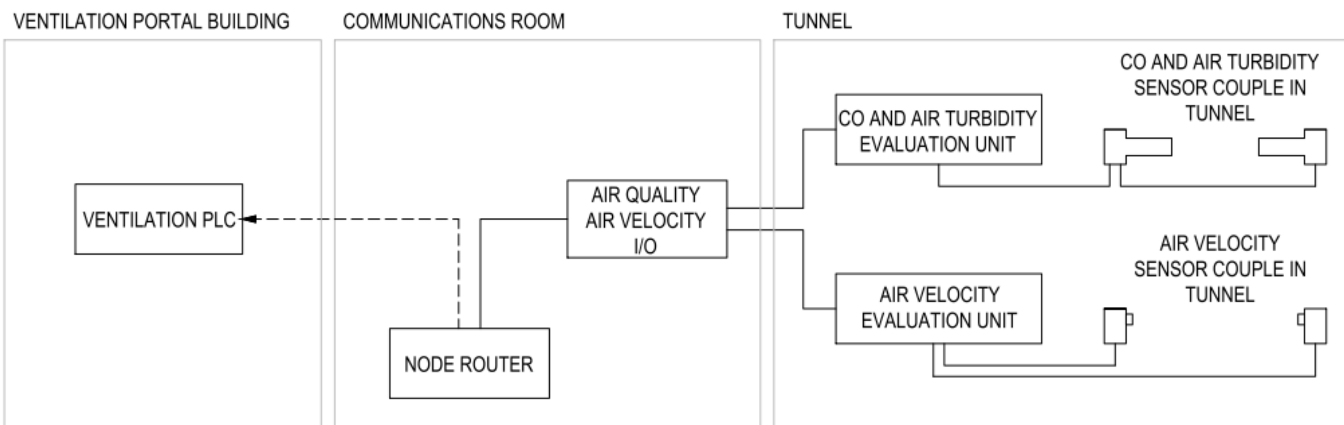


Figure 7: Typical Monitoring Configuration

Maintenance requirements for tunnel sensors are minimized. Sensors must be ruggedized for the harsh tunnel environment and located such that no traffic control is required for access. All instruments, and particularly gas detectors, tend to drift over time, requiring re-calibration. Automated calibration features in the monitoring system minimize the cost of field calibrations performed on the roadway.

3.6.1 Carbon Monoxide (CO) Monitoring

Carbon monoxide is the primary toxic gas of concern for monitoring in tunnels. In fact, the potential for hazardous exposure to carbon monoxide is a distinctive criterion for Caltrans for defining a structure as a tunnel. CO sensors are mounted on the tunnel walls every 300 to 350 feet in both tunnel tubes on both decks. CO concentration is measured by to detect and alarm concentrations. NFPA 502 (B.2.2) gives the following limits for CO:

- Maximum of 2,000 ppm for a few seconds
- Averaging 1,150 ppm or less for the first 6 minutes of the exposure
- Averaging 450 ppm or less for the first 15 minutes of the exposure
- Averaging 225 ppm or less for the first 30 minutes of the exposure
- Averaging 50 ppm or less for the remainder of the exposure

3.6.2 Visibility (Air Turbidity) Monitoring

Visibility in tunnels is affected by particles in the air such as fog, smoke, dust or exhaust fumes. Turbidity sensors determine visibility by measuring the light scattered by these particles.

According to the NFPA 502 (B.2.3) the smoke obscuration levels must be continuously maintained below the point at which a sign internally illuminated with a luminance of 8.6 cd/m² (2.5 fl) is discernible at 100 feet (30 m) and doors and walls are discernible at 33 feet (10 m). Even though the fire detection system will typically detect a fire before the air turbidity sensors detect obscuration, some fires produce smoke without much heat. In principle, obscuration could be sufficient for the air turbidity sensors to activate the ventilation system first to begin clearing the air.

Turbidity sensors are co-located with CO sensors approximately every 3000 feet on both decks. Certain units may combine monitoring of visibility and CO in a single unit. The carbon monoxide and smoke obscuration measurement system (CO-SO measurement system) must be located near the vehicle cross passages to reduce the cable length to the evaluation unit housed in an electrical niche. The first CO-SO measurement point must be installed about 350 feet from the tunnel entrance.

Certain smoke detectors work by the same principle of light scattering. Although visibility sensors can also be used for early fire detection, separate smoke detectors must be dedicated for fire detection. See the fire detection section for details.

3.6.3 Air Velocity Monitoring

Tunnel air velocity is a critical parameter to be controlled, both during normal operation and in the event of a fire.

> NFPA 502 11.2.3: *In tunnels with bidirectional traffic where motorists can be on both sides of the fire site… (2) Longitudinal air velocity will be kept at low magnitudes.*

> NFPA 502 11.2.4: *In tunnels with unidirectional traffic where motorists are likely to be located upstream of the fire site, the following objectives will be met: (1) Longitudinal systems (a)*Prevent backlayering by producing a longitudinal air velocity that is calculated on the basis of critical velocity in the direction of traffic flow.*

To prevent hazards, traffic speeds are reduced and jet fans operated opposite to traffic direction when air velocity is sufficiently high with exposed motorists or personnel on the roadway. According to the NFPA 502 (B.2.4), the air velocities in the enclosed tunnel must be kept between 150 feet/min and 2,200 feet/min.

Air velocity and air flow direction are measured by ultrasonic sensor couples every 2,625 feet, mounted 15 feet above the deck on both roadways.

3.6.4 Hydrocarbon Detection

Hydrocarbons such as spilled fuel in the tunnel drainage system are detected in the drainage sumps and pump stations. Detection initiates a local alarm near the pump or sump and a remote alarm to the OCC. The hydrocarbon detection system transmits alarms and status through the SCADA system. Hydrocarbon detectors are only required for the drainage system. These requirements are found in NFPA 502.

> NFPA 502 7.12.7.1: *Storage tanks and pump stations will be monitored for hydrocarbons.*

> NFPA 502 7.12.7.2: *Detection of hydrocarbons in the tunnel drainage effluent will initiate both a local and a remote alarm.*

3.7 Electrical Systems

The following describes the requirements and proposed electrical system for the tunnel including the overall power and emergency power system.

3.7.1 Power System

The power supply system includes the medium voltage and low voltage system for the supply of electrical components including lighting, ventilation, pumps, and other fire/life safety equipment. The electrical system is designed as a Category D system according to NFPA 502 requirements. The system must support life safety operations, fire emergency operations, and normal operations, and is designed as a redundant electrical system with two independent power connections from two separate utilities on the north portal and a voltage of 17 kV.

The electrical system also allows routine maintenance without disruption of the traffic in each tube.

In case of a breakdown of the main power supply, the emergency power system supplies uninterrupted power for the critical loads (for example, fire/life safety related equipment).

The dual feed-in primary power supply is realized as a medium voltage 17 kV system. The feed-in is at the north portal from two independent sources, and the medium-voltage distribution will be fed by 34.5kV cable lines. The energy is provided by the Power Supply Business Unit (PSBU) of the City of Pasadena.

The main power supply distribution will be installed in the north portal ventilation building. There is a room with reserved access to the equipment installed and maintained by the PSBU of the City of Pasadena. Circuit breakers and measurement equipment are stored in this room to supply the tunnel with energy. Nearby, a medium voltage room is placed to distribute the energy. From this position, cables run to the different communications rooms in the tunnel and further to the south portal ventilation building.

Cast-resin, dry-type transformers convert the medium voltage to low voltage (480V/277V) or (690V/480V) for the ventilation system. The 480V/277V voltage level is used for the power supply of the lighting system, ventilation system, pumps, and other fire/life safety equipment. Other distribution transformers supply power to the monitoring and control systems at a voltage of 208V/120V.

An operation building and an electrical substation will be situated close to each tunnel portal. Distribution transformers are placed at each building for medium- and low-voltage distributions. Each electrical substation will be provided with utility feeders for the tunnel power supply.

Communications rooms are located near every vehicle cross passage (approximately every 3,000 feet) between the upper and lower decks on their own platforms. These communications rooms consist of transformer rooms, medium-voltage rooms, low-voltage rooms, rooms for UPS and batteries, and rooms for the fire/life safety equipment.

A power metering system on the low voltage side records energy consumption of the individual systems such as ventilation, lighting (threshold, interior and total lighting), UPS, general electrical equipment and total energy for the tunnel.

3.7.2 Emergency Power System

An online uninterruptable power supply (UPS) provides power to critical loads for which a momentary power outage or interruption is not acceptable. This includes emergency lighting, tunnel closure and traffic control, exit signs, emergency communications, tunnel drainage, fire alarm and detection, CCTV, and the fixed firefighting system. The emergency circuits must remain functional for a period of not less than one hour.

The UPS units are designed to operate "online" such that when the normal power fails, the batteries provide power for certain systems for a designated period. If a UPS malfunctions, the power automatically connects the load directly to the normal supply while opening the output power side of the UPS. A maintenance by-pass can manually transfer the load to the normal supply for routine service or maintenance of the UPS.

The UPS rating and battery size is estimated by means of calculations for the intended load.

The table below shows the different levels of emergency power and the loads supported.

Table 2: Emergency Power Levels and Supported Loads

Tunnel Load	Level 1: Second Utility Source	Level 2: UPS
Tunnel Ventilation	All fans	No fans
Tunnel Lighting	All lighting	Tunnel emergency lighting
Egress Walkway Lighting	All lighting	Egress walkway emergency lighting
Utility Corridor Lighting	All utility corridor lighting	Utility corridor emergency lights
Drainage	All drainage pumps	No pumps
Fire Detection and Fire-Fighting Systems	All fire detection and fire-fighting systems	Fire alarm systems
Voice Communications Systems	All voice communications systems	All voice communications systems

Data Transmission and Control Systems	All data transmission and control systems	All data transmission and control systems
Traffic Detection and Control Systems	All traffic detection and control systems	All traffic detection and control systems
Tunnel Environmental Monitoring	All tunnel environmental monitoring	All tunnel environmental monitoring
Security Systems	All security systems	All security systems
Portal buildings	All building functions	Emergency lights, fire alarm systems, Building emergency equipment

3.8 Lighting Systems

The following sections explain the proposed lighting system for the tunnel including the overall lighting and the emergency lighting system.

3.8.1 Overall Lighting System

The overall lighting system is divided into three different zones: the threshold zone, the transition zone, and the interior zone. Each zone has different lighting parameters and characteristics defined to accommodate the eye adjustments needed by motorists transitioning from outside to interior brightness levels.

A step down method is used as a practical way to gradually reduce the luminance in the threshold and transition zones to the level in the interior.

The threshold zone helps the eye to adapt to the darkness inside of the tunnel. The length of this zone depends on the traffic speed limit and the safe stopping sight distance (SSSD). The luminance in the threshold zone can be adjusted with respect to changes in the exterior luminance. The threshold zone is divided into two steps. The second step has a lower luminance and lasts two seconds.

For the threshold zone, lighting luminaries are installed on the tunnel ceiling along two rows.

The transition zone helps the eye to adapt to the low luminance in the interior zone. The luminance at the beginning of the transition zone is equal to that at the end of the threshold zone. The luminance is gradually reduced to the level of the interior zone towards the end of the transition zone. Depending on the travel speed, there are additional steps in the transition zone. The length of each step is increased by one second, starting with three seconds for the first transitional step. There can be up to three steps in the transition zone. The luminance ratio between the steps must not exceed 2.5.

The interior zone has the lowest luminance in the tunnel and is divided into several sections. Each section is supplied by the low-voltage network from the nearest communications room. At night, the luminance can be reduced to 2.5 cd/m^2. According to ANSI/IES RP-22-11 the uniformity ratio of the interior lighting must be 2 to 1, average-to-minimum, and 3.5 to 1, maximum-to-minimum.

For specific recommendations about lighting fixtures, see Appendix C, Lighting System: Lamp Type Selection.

3.8.2 Emergency Lighting System

Emergency lighting must meet specific requirements including fire-resistant cabling, minimum illumination levels, time for supply interruption and uniformity ratio. For emergencies, lighting is augmented with escape path marking to guide pedestrians to emergency exits.

To fulfill the category D requirements defined in NFPA 502, emergency lighting must be supplied by fire-resistant cable or an embedded cable with protection lasting two hours. The emergency lighting is installed in each lighting zone of the tunnel and has a minimum average illumination level of 10 lx. The illumination must not be less than 1 lx, and the maximum-to-minimum illumination uniformity ratio of the emergency lighting cannot be greater than 40 to 1.

To ensure the function of the emergency lighting in case of power failure, the system must be connected to the emergency power supply from the emergency distribution boards at the nearest communications room and be wired in separate cable ducts. Supply interruptions cannot be greater than 0.5 seconds. Inside the emergency walkway, emergency lighting is supplied by the UPS. To fulfill California building code energy savings requirements, emergency pathway lighting is motion activated to turn on lighting only when the space is occupied.

This page intentionally left blank.

4. Fire Life Safety Systems

4.1 Overview of the Fire Life Safety Systems

This section describes the mechanical systems provided for ensuring the health and safety of motorists and personnel for the freeway tunnel alternatives. Generally, the mechanical systems requirements are equivalent for the dual and single bore freeway alternatives. The recommended mechanical systems and equipment are broadly categorized as follows:

- Fixed Fire Fighting System (FFFS)
- Standpipe and Hose System
- Co-Location of First Responders
- Fire Extinguishers
- Tunnel Ventilation System

Fire life safety systems must meet the requirements of NFPA 502. Per NFPA Annex E, considerations for the Fire Suppression System should include the ventilation regime (2) Tunnel height (3) Nozzle installation height (4) Expected fire load (5) Environmental conditions (e.g., corrosion and freezing) (6) Water application rate.

> Fire Protection Handbook, Section 21, Chapter 11: *One of the major factors to be considered in the fire protection of a road tunnel is the unknown nature of the potential fire load. … for the typical road tunnel, where an innocent-looking truck may be carrying a load that is capable of supporting a fast-growing, potentially lethal fire, but that is not necessarily "classified" as hazardous cargo.*

Several coordination meetings with the LA Fire and Police Departments were conducted to determine the design relevant heat release rates and fire growth curves. Fire scenarios included the possibility of a fire spreading from one vehicle to another. Validation testing of the system is recommended in final design or implementation stages. If the FFFS is unavailable, the ventilation system is designed for a 100 MW dry fire.

The following design fire properties were used for the design and modeling of the FFFS and Tunnel Ventilation System:

- Peak Fire Heat Release Rate: 100 MW
- NFPA 204 criteria
- Fire Smoke Release Rate based on an air / fuel ratio of 14.3
- Soot Yield Rate of 0.179 grams soot / grams fuel

Based on the modeling and analyses the FFFS be designed as a deluge foam water system as specified in NFPA 16, the standard for foam-water sprinkler systems. As recommended by the fire marshal, the FFFS will flexibly allow water only for heavy goods vehicle fires or water plus foam for fighting liquid fuel fires. Foam concentrate and water is pumped separately from the north OMC building throughout the tunnels. The foam concentrate and water is mixed proportionally in each of 226 zones per roadway. In addition, a standpipe and hose system supplies fire water for up to one hour, as specified in NFPA 14 and NFPA 502.

The combination of the FFFS, three independent fire detection systems, and a ventilation system designed for 100 MW will allow compressed natural gas (CNG) buses in the tunnels.

4.2 Fixed Fire Fighting System (FFFS)

The following is an overview description of the FFFS. The FFFS consists of the Standpipe and Hose System and the Deluge Foam Water System. The standpipe and hose system is designed as a Class I system according to NFPA 14. The deluge foam water system is designed according to NFPA 16.

> Fire Protection Handbook, Section 21, Chapter 11: *In road tunnels, fixed fire-fighting systems are defined as consisting of fire-fighting equipment, permanently attached to the tunnel, consisting of a piping system with a fixed supply of water or extinguishing agent which, when operated, has the intended effect of reducing the heat release and fire growth rates by discharging the water or extinguishing agent directly on the fire. Examples of fixed fire-fighting systems include sprinkler and deluge systems.*

4.2.1 Water and Foam Provisions

Water storage for the deluge foam systems must be a minimum of 120,000 gallons as required by NFPA 16 for a duration time of 60 minutes across three zones.

For the standpipe and hose system, a flow rate of 500 gpm and a duration time of 60 minutes is required by NFPA 14, chapter 7.10.1.1.1. To meet this requirement, the water supply tank must hold at least 30,000 gallons. This provisioning considers a fire on one deck (upper or lower deck) in one tube (north or south bound).

A total water reservoir of 120,000 + 30,000 = 150,000 gallons must be provided at minimum.

The foam concentrate is stored in two “intermediate bulk containers” (IBC) with 330 gallon each for easy handling. With two containers, IBC foam can be generated for 10 minutes across three zones with an additive of 1 - 3%.

4.2.2 Standpipe and Hose System

The Standpipe and Hose System is designed to fulfill the requirements of NFPA 14 and NFPA 502.

> *According to NFPA 502, a Class 1 standpipe system is required in all road tunnels over 300 feet (90 m) in length. The system should be of the wet type. As specified in NFPA 502, the road tunnel standpipe system must be designed to provide support to a minimum of two fire hose streams delivering 250 gpm (16 L/sec) each. The standpipe system must be installed in accordance with NFPA 14, Standard for the Installation of Standpipe and Hose Systems.*
>
> *The water supply system, whether municipal or private, should have adequate water flow and pressure along with the required system integrity. The water supply system considered should have a minimum supply capacity of one hour of fire fighting as prescribed by NFPA 502 and should be configured in accordance with NFPA 14. If a storage tank is required to meet the water supply capacity, it should be installed in accordance with NFPA 22, Standard for Water Tanks for Private Fire Protection.*
>
> *According to NFPA 502, standpipe hose connections or hose valves should be installed in the road tunnel, so that no point on the protected tunnel roadway is more than 150 feet (45 m) from an active hose valve.*

The Standpipe and Hose System consists of two individual standpipe cycles and must be able to deliver water for firefighting for up to one hour. A jockey pump supplies the required pressure for the whole system (both tunnels, upper and lower deck). In case of a fire alarm, the firefighting pump is activated by the control system. Water extraction occurs through fire hose connections.

The major components of the Standpipe and Hose System are:

- Two jockey pumps (operation mode 1+1)
- Two firefighting pumps (operation mode 1+1)
- Fire hose connections
- Two pressure regulating stations (for each deck)

The standby system is designed as a wet pipe. Because of the warm weather conditions throughout the year, no special requirements are needed to prevent the freezing of the fire water in the water line. The standpipe system must be connected to a municipal or privately-owned waterworks system. To guarantee that there is enough fire water available in the event of fire, a water basin must be located at the tunnel portal located at a higher elevation.

The water basin supplies two individual standpipe headers. The first header comprises fire pumps that produce the required pressure for the hose connections inside the tunnel. This standpipe header is required to supply the first part of the tunnels with fire water. This first fire water header supplies the fire water for both tunnels, upper and lower deck.

The second fire water header pipe, which is connected to the water basin, makes use of the difference in height between the upper and the lower tunnel portals. No fire water pumps are necessary to produce the required pressure and flow at the hose connections. The header pipe shall supply the upper and lower decks of both tunnels with fire water. In the lower section of the tunnels, throttle valves are required to reduce the flow rate to the required values as specified by NFPA 14.

4.2.2.1 Hydraulic

Due the altitude difference between the north portal and the lowest point of the main water pipe the maximum pressure of 175 psi at a 1.5 in. (40 mm) outlet on a hose connection cannot be guaranteed as requested by NFPA 14 under chapter 7.8.3.1, as a minimum pressure of 100 psi is required (on north portal).

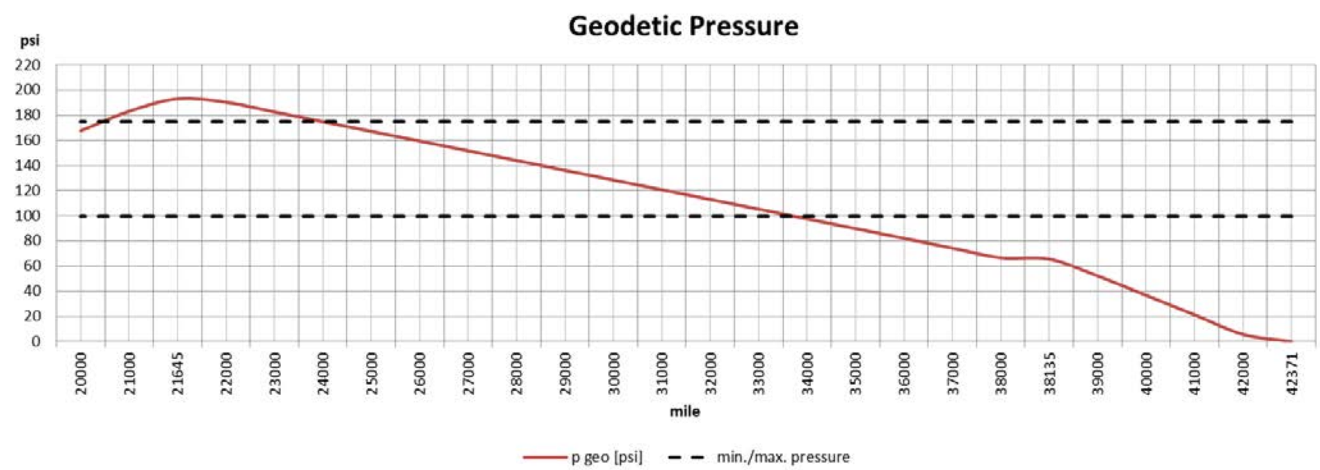


Figure 8: Geodetic Pressure

To reach a minimum pressure of 100 psi as requested by NFPA 14, the pressure at the North Portal must be boosted by pumps.

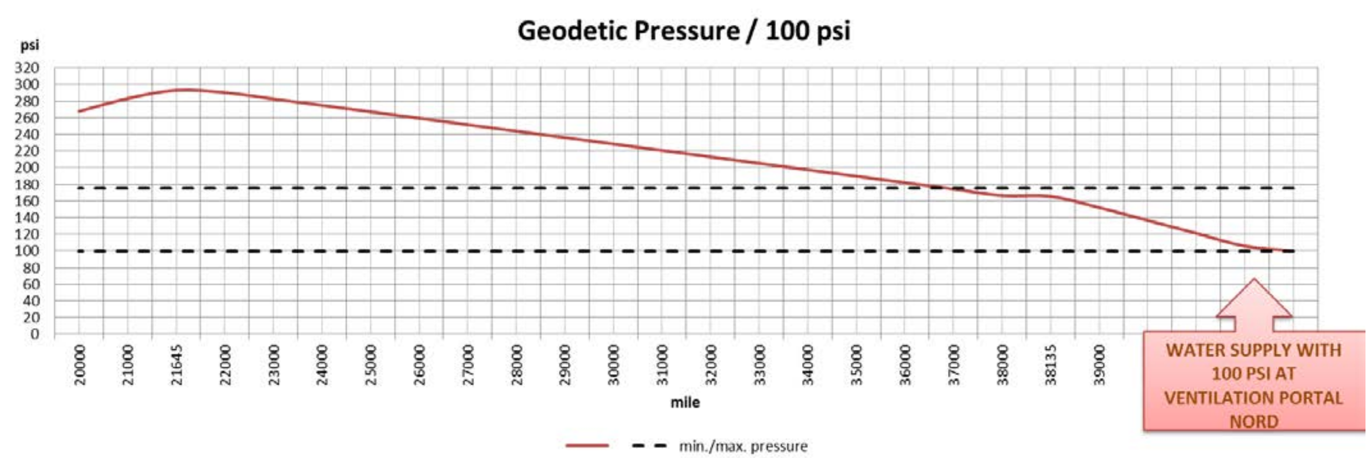


Figure 9: Geodetic Pressure with Increased Pressure to 100 psi

As shown in the preceding figures, the geodetic static pressure from just the altitude difference is insufficient for the requirements of NFPA 14.

To achieve the requirement for the maximum pressure at the outlet on a hose connection, the Standpipe and Hose system is split in three branches. Each pressure regulating station is designed in a duty/standby mode. This means that there are two pressure regulating valves for each pressure regulating station. If one fails the other one is working.

- The first branch, from mile 42.37 to 37.00, supplies water for the first 5,370 feet of tunnel. For the necessary minimum design pressure of 100 psi as required by NFPA 14 chapter 7.8.1, a fire water pump must be provided.
- At the end of the first branch, a pressure reducing station is needed to reduce the pressure to 100 psi.
- The second branch must start at 100 psi and must not exceed the maximum pressure of 175 psi up to mile 28.00.
- At the end of the second branch, at mile 28.00, a pressure reducing station is needed to reduce the pressure to 100 psi.
- The third branch starts at mile 28.00 and the pressure must not exceed the maximum pressure of 175 psi until the end of the main pipe on the south portal.

Pressure conditions of the three branches can be seen in the following picture:

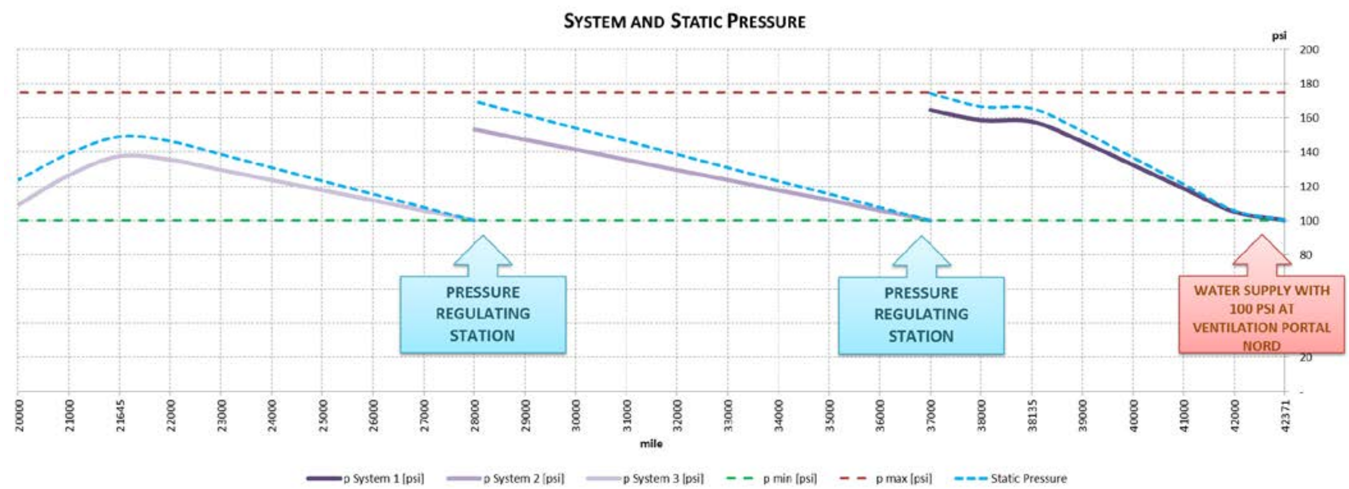


Figure 10: Pressure conditions in the braches of Standpipe and Hose System

Figure 10 shows the system pressure of the proposed standpipe systems. The system pressure has to be at least 100 psi and not more than 175 psi according to NFPA 14. Through the zoning of the water main pipe in three branches, the requirements of NFPA 14 are met. The standpipe system is a “Class 1” system to meet the requirements of NFPA 14.

4.2.2.2 Piping and Instrumentation Diagram (PID)

The PID of the standpipe system is provided in the drawings on Wet Standpipe / Hydrant System Schematic.

4.2.2.3 Pipe Materials

Ductile-Iron pipes according to AWWA C151 with Cement-Mortar Lining according to AWWA C104 are used for the standpipe systems. The connection is a push-in joint.

4.2.2.4 Water Provision

A water amount of at least 30,000 gallon can be calculated and is required according to NFPA 14, chapter 7.10.1.1.1, for a flow rate of 500 gpm and a duration time of 60 minutes. The provisioning considers a fire on one deck (upper or lower deck) in one tube (north or south bound).

4.2.2.5 Pumps

Pumps must meet the following requirement:

> NFPA 502 10.5 *Fire pumps shall be installed, inspected, and maintained in accordance with NFPA 20*. Also the Fire Protection Handbook states: *When fire pumps are required to provide the necessary flow capacity and pressure in the road tunnel standpipe system, they should be installed in accordance with NFPA 20, Standard for the Installation of Stationary Pumps for Fire Protection.*

The pump station is located in the north portal building. For the standpipe system, two stationary fire water pumps are provided. The pumps have a flow rate of at least 500 gpm and a pump head of at least 100 psi. Jockey pumps are also required with 65 gpm and at least 100 psi.

Pumps start when the pressure in the main pipe drops down. The jockey pump raises the pressure in the main pipe to 100 psi. The main fire pump starts when the pressure continues to drop.

All necessary fire pumps for the standpipe system are electrically driven to fulfill the requirements of NFPA 20. The pumps operate in a duty/standby configuration, which means that one pump shall always be available if one of the other pumps fails.

4.2.2.6 Fire Department Connections

Two fire department connections (FDC) must be provided for the standpipe-system. One FDC is to be located at the North Portal and the other at the South Portal. The layout of the FDCs fulfill NFPA 14 requirements. FDCs shall be according to the NFPA 502 10.3 Fire Department Connections.

> Fire Protection Handbook, Section 21, Chapter 11: *Fire department connections are required to allow the fire department to charge the standpipe line. Two connections should be provided for every standpipe system and installed in accordance with NFPA 14. Each fire department connection should be installed within 100 feet (30.5 m) of an active hydrant that is tied into an approved water supply.*

4.2.2.7 Drainage

Drainages are provided on the pressure regulating stations and on the lowest point of the main pipe. The drainages are connected to the tunnel drainage.

4.2.2.8 Maintenance Valves

For maintenance purposes, gate valves in the main pipe are needed. The maximum spacing between gate valves cannot exceed 2,000 feet. These valves make it possible to shut off sections of the main pipe to allow maintenance without draining the entire system.

4.2.2.9 Fire Hose Connections

Water is extracted by hose connections. Each hose connection is located in the hose valve cabinet (HVC). The maximum distance between HVC´s can be 275 feet as specified in NFPA 502, chapter 10.4.2. Each HVC consists of two 2 1/2” hose valve assemblies, a 4-inch gate valve, an automatic trap drain and the 4” hydrant hose connection. The HVC will be located in a niche. The layout of the HVC is as specified in NFPA 14.

4.2.2.10 Air Relief Valve

Automatic Air Relieve Valves have been foreseen on the peaks of the main pipe as in the Pressure Regulating Stations.

4.2.2.11 Pressure Regulating Station

The station operates in a duty/standby configuration. The main components are:

- Gate valves for maintaining the pressure reduce valve
- Strainer
- Pressure reducing valve
- Pressure transmitter for monitoring the function of the system

- Drainage

4.2.3 Deluge Foam Water System

The freeway tunnel is designed with a fixed fire fighting system as per the requirements of the NFPA, which says that this system must be installed when vehicles downstream of an incident site cannot be evacuated under all traffic conditions. Because of the heavy traffic expected in the tunnel, it is not possible to clear the traffic downstream of the fire site under all conditions. The Deluge Foam Water System shall be designed and calculated to be sufficient to handle the expected fire loads.

The Deluge Foam Water System is the second fixed firefighting system for the roadways. Nozzles are situated at the top of the roadway in four parallel running rows capable of discharging water or foam. Nozzles are grouped into 226 deluges zones per roadway, each with approximately 115 feet of coverage. The system must be sized to allow simultaneous discharge of three adjacent deluge zones. In case of a fire, the zone in which the fire is detected and the two nearby (before and after) are activated. After motorists are evacuated, foam can be activated by the operator to assist fire fighters with extinguishing the fire. The system can be operated from either Operations Control Center.

Operation. In accordance with NFPA 72 6.8.1.3, Positive Alarm Sequence, a fire alarm from the fire detection systems (except for the linear heat detector) can be acknowledged by the tunnel controllers within 15 seconds. They can then visually investigate by CCTV whether the fire is an actual or a false alarm. Because the linear heat detector is reliable for not having false alarms, the FFFS can be triggered immediately. However, issues with immediately putting the deluge on moving traffic should be considered as a design issue in later stages.

Tunnel operators have up to 60 seconds during the alarm investigation phase to evaluate the fire condition and reset the system. (The 60 second window is nominal at this stage and should be reevaluated in later design stages.)

As shown in Figure 11, Positive Alarm Sequence, the FFFS is automatically activated upon:

- Alarm in from Operator or Linear Heat Detector
- Operator confirmation of fire
- 15 seconds elapsed with an unacknowledged fire detection by CCTV or Smoke Detector
- Second detection by CCTV/Smoke detector
- 60 seconds elapsed with no reset

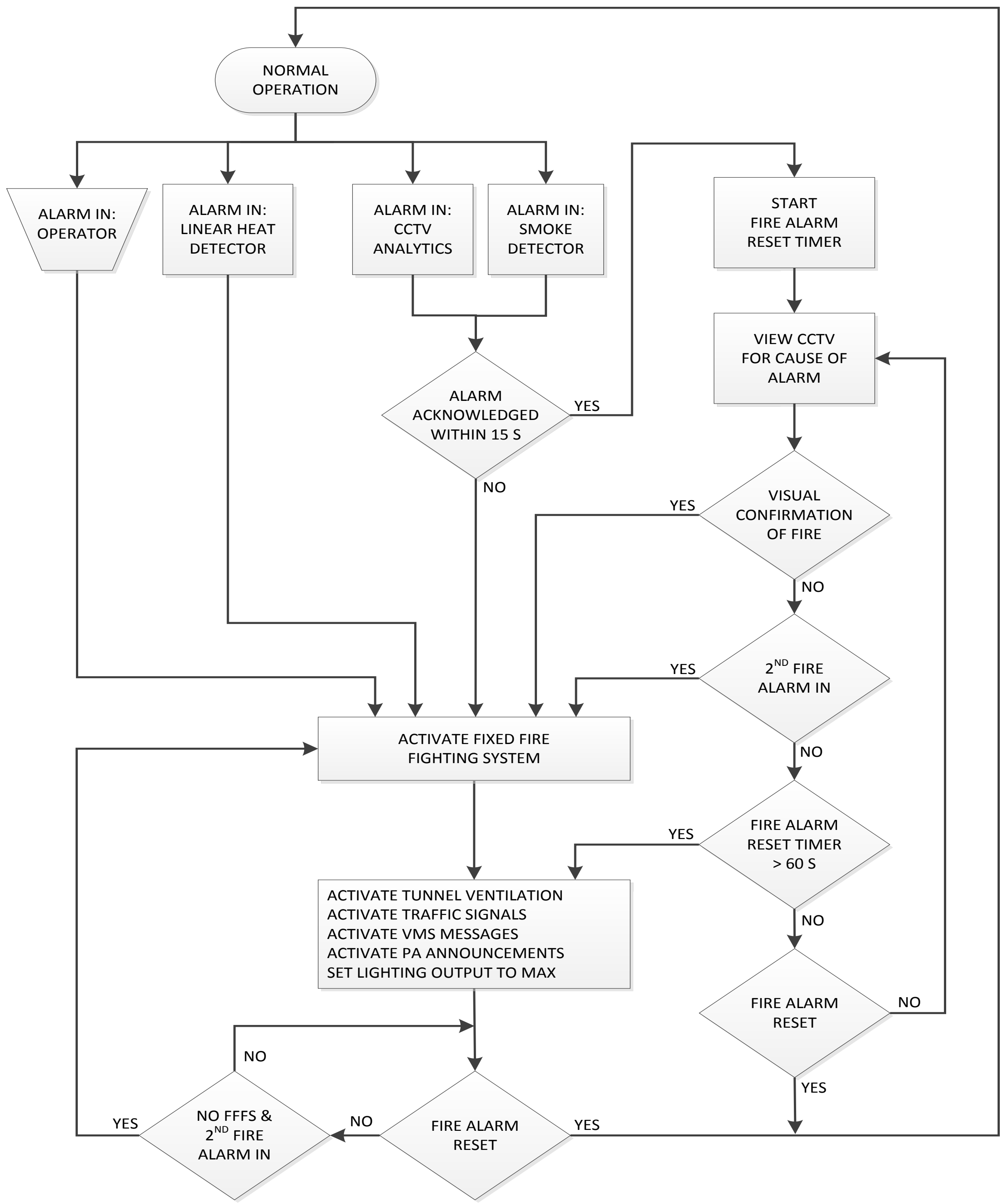


Figure 11: Positive Alarm Sequence

When the FFFS is activated as described in the Positive Alarm Sequence in Figure 11, a sprinkler pump is started immediately to pressurize the fire water header. If the first pump fails, the other pump is automatically started.

After the sprinkler pump is running, the magnetic valves for the appropriate deluge zone(s) are opened.

Water continues to be discharged in the deluge zone until the tunnel operator takes an action.

The operator can command the foam concentrate pump to start. After the foam concentrate pump is running, the foam valves open automatically for the appropriate zones for mixing with the deluge water.

Alternatively, the operator can command the deluge or foam to stop.

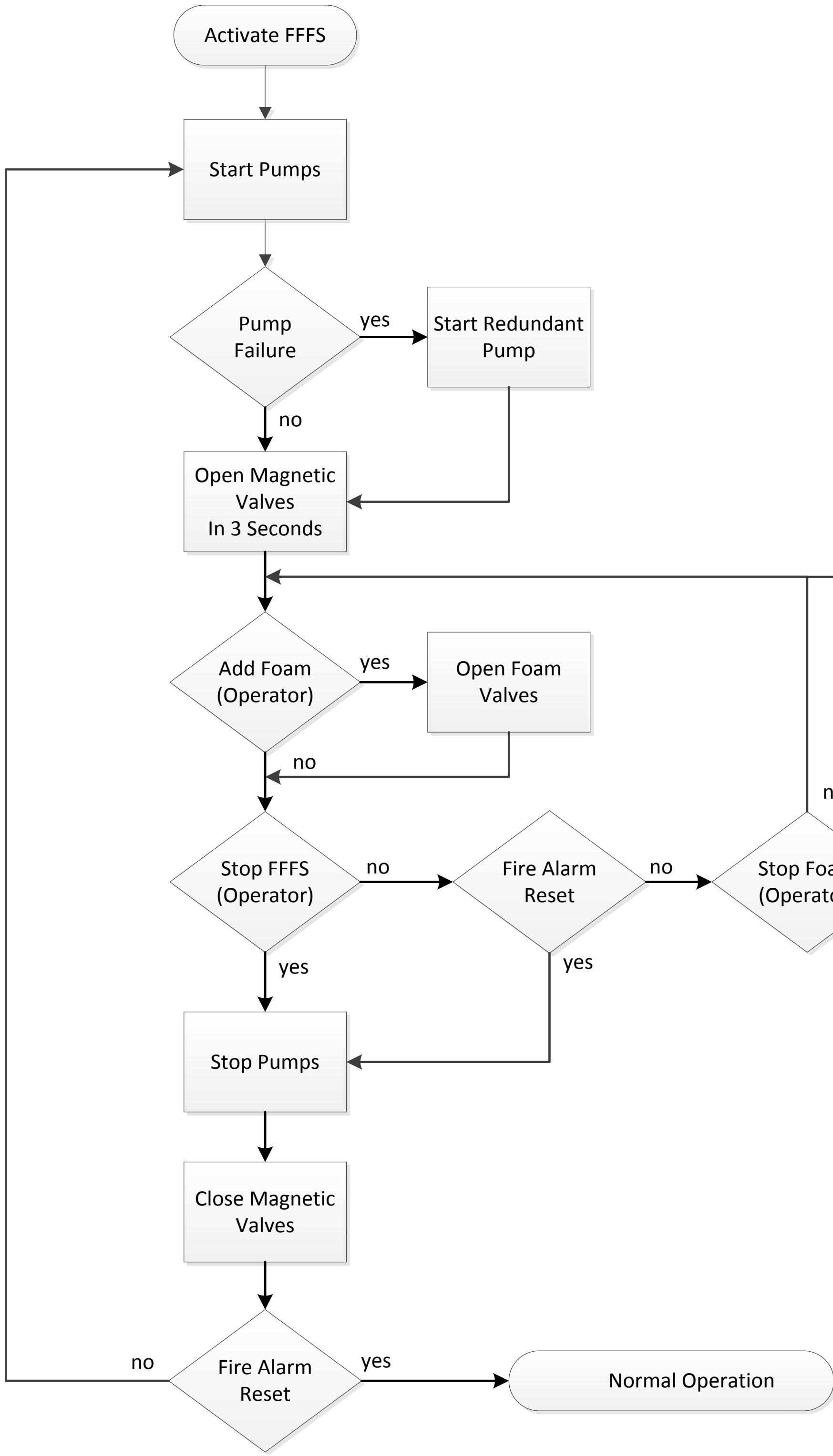


Figure 12 FFFS Activation Sequence

4.2.3.1 Design Parameters

Pumps. The installation provides redundant pumps such that loss of one pump does not reduce the system's ability to deliver the design performance.

All necessary pumps for the Deluge Foam Water System are driven electrically to fulfill the requirements of NFPA 20.

Maintenance Valves. Maintenance gate valves are foreseen in the branches. The maximum spacing between valves cannot exceed 2,000 feet. These valves enable shut off of pipe branches in sections to allow maintenance without draining the entire system.

Drainage. At the lowest point of the pipes, there is a 2 inch drainage valve. The drainage is connected to the tunnel drainage.

Inline Balance Pressure Proportioner (ILBT). The ILBP is a completely self-contained device containing all necessary components. Foam concentrate balancing is achieved through two sensing lines, one from the water supply and one from the foam concentrate pipe. Both lines are connected to the diaphragm valve. The diaphragm valve automatically adjusts the foam concentrate pressure to correspond to the water pressure. The foam concentrate is then metered through a fixed orifice into the water stream.

Foam Provision. The foam concentrate is stored in two “intermediate bulk containers” (IBC) with 330 gallon capacity for easy handling.

Table 3: FFFS Design Parameters

Sprinkler Pumps	
Quantity	2
Type	Electrically Driven
Operational Mode	Duty/Standby
Minimum Flow Rate	1990 gpm
Minimum Pressure	185 psi
Location	North Portal Building

Foam Concentrate Pumps	
Quantity	2
Type	Electrically Driven
Operational Mode	Duty/Standby
Flow Rate per Pump (varies with concentrate)	20 - 60 gpm
Minimum Pressure	80 psi
Location	North Portal Building

Deluge Foam Valve Stations	
Quantity	1 per Deluge Zone
Location	Egress Walkway

Foam Concentrate Tanks	
Quantity	2
Capacity	330 gal
Location	North Portal Building

Fire Water Basin	
Total Capacity	150,000 gal
Designated to Foam Water Deluge	120,000 gal
Designated to Standpipe and Hose System	30,000 gal
Location	North Portal Building

4.3 Co-location of First Responders

In addition to the normal tunnel control operations centers at the OMC buildings, accommodations for 24-hour staffing of first responders at both portals are included. These crews with foam fire fighting vehicles ready at the portals will reduce response times to a minimum. Except for the Eisenhower Johnson Memorial Tunnel in Colorado, no other tunnels in North America have been identified with co-located fire response crews.

For more information, see Appendix B.

4.4 Fire Extinguishers

Portable fire extinguishers with a rating of 2-A:20-B:C and a total maximum weight of 20 pounds are located in the hose valve cabinet (HVC). Fire extinguishers are required, as specified by NFPA 502.

SECTION 5

5. Tunnel Ventilation System

During normal operation, the tunnel ventilation system's primary function is to reduce the level of harmful gases, particularly carbon monoxide (CO).

During a fire, the tunnel ventilation system is designed to remove smoke and harmful gases during a tunnel fire. Working in conjunction with the Fixed Fire Fighting System (FFFS), the ventilation system controls smoke and gases during a fire. Ventilating the smoke and gases maintains a tenable environment for the evacuation of motorists, and for the safe entry into the tunnel by firefighters.

The ventilation system must have redundancy such that loss of one fan does not reduce the system's ability to deliver the required performance. With a single fan system, downtime for maintenance could require a partial closure of the tunnel.

5.1 Overview of the Ventilation System

The ventilation concept for normal operation is longitudinal ventilation using jet fans. In the case of a fire, the concept allows smoke extraction locally with automated exhaust dampers. Ventilated emergency walkways are provided along the tunnel. There are air scrubbers at the exit portals of both tunnels.

Figure 13 shows a schematic of the tunnel system. Both tunnels show a double deck and jet fans in the cut and cover section. Parallel to the traffic area, the exhaust duct is connected through dampers to the exhaust fans at the portals. The by-pass for air scrubbing is as indicated.

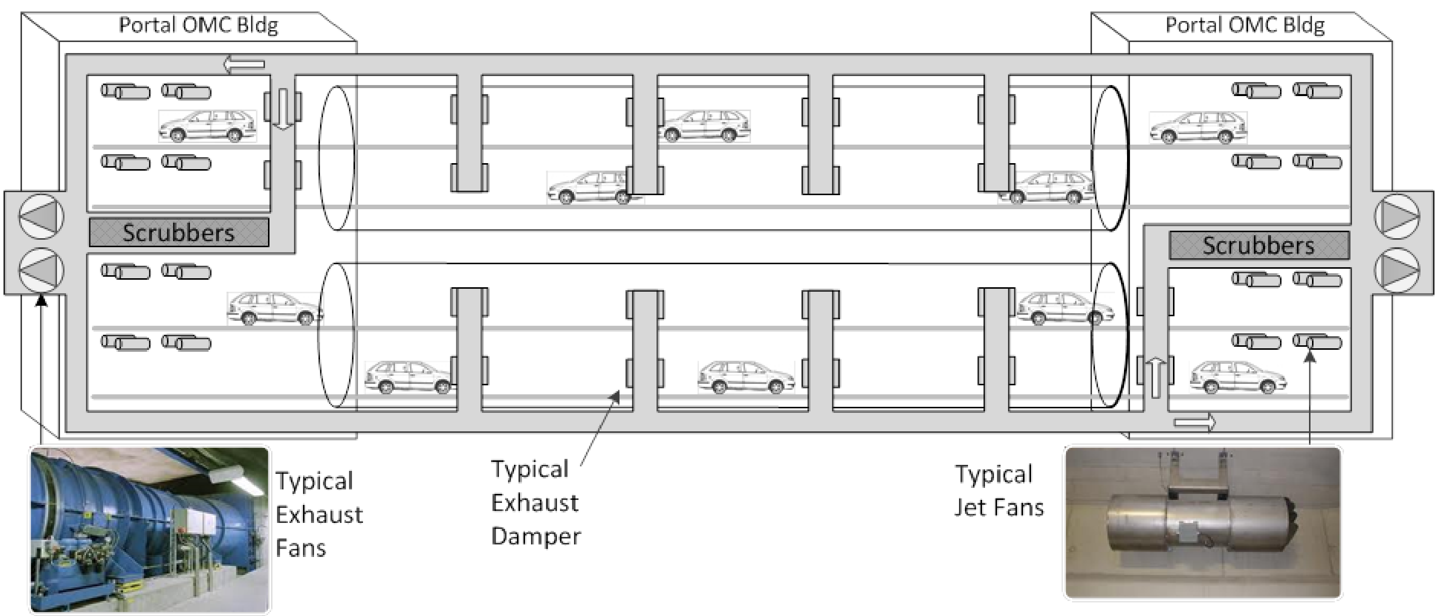


Figure 13: Schematic Representation of the Ventilation System

5.2 Ventilation System Objectives

The ventilation system must meet the following requirements:

> Fire Protection Handbook, Section 21, Chapter 11: *In a road tunnel, smoke management requires either direct extraction at the fire site or the generation of a longitudinal velocity in the tunnel capable of transporting the smoke and heated gases in the desired direction to a point of extraction or discharge from the tunnel. Without a smoke management system, the direction and rate of movement of the smoke and heated gases will be determined by fire size, tunnel grade, pre-fire tunnel conditions, and external meteorological conditions.*

> *The primary purpose for controlling smoke in a tunnel is to protect life and to permit safe evacuation of the tunnel. This involves creating a safe path of egress for both motorists and any operating personnel located within the tunnel when the fire starts. The secondary purpose of smoke control ventilation is to assist fire fighters in accessing the fire site, by again providing a clear path to the fire site if possible.*

Normal operation includes every traffic situation from free flow traffic to standstill situation without a fire. The ventilation system is designed to maintain air quality limits in the tunnel under all conditions. Monitoring systems for CO and visibility in the traffic area continuously monitor air quality and can trigger ventilation system responses through SCADA if thresholds are reached.

Ventilation criteria were developed for both the normal and emergency operational modes of the tunnel. During normal operation, the main ventilation aims are to:

- Maintain air quality at acceptable values to ensure safe driving and to avoid health risks to tunnel occupants
- Avoid concentration of noxious gases outside the tunnel at the portal areas

With reference to PIARC recommendations, these general aims are translated into threshold values which are summarized in Table 8-1.

Table 4: Normal Operation: Threshold Values for Ventilation System

Parameter	Threshold Value for Normal Operation
CO-concentration	70 ppm
Visibility, extinction coefficient	5 / km (60% transmission for a light beam with 100 m)
NOx	n/a

In the case of emergency operation, the main ventilation aims are to:

- Remove and control smoke and heated gases
- Maintain a smoke-free environment along the escape path

NPFA 502 contains the specific ventilation criteria that were used to develop the ventilation designs presented in the following sections. Table 8-2 summarizes the emergency operation ventilation criteria.

Table 5: Emergency Operation: Threshold Values for Ventilation System

Parameter		Threshold Value for Emergency Operation
Longitudinal flow velocity from entrance portal to incident location		Critical velocity
For systems with smoke extraction:	Longitudinal flow velocity from exit portal to incident location	> 0
	Exhaust air flow rate	According to design HRR and longitudinal flow velocities on both sides of the incident location

5.3 History of the Ventilation System

In 2006, LA Metro commissioned a feasibility study to determine if tunneling would be a viable option. The conceptual evaluation of the tunnel ventilation system included intermediate ventilation shafts along the tunnel alignment, as shown in Figure 14.

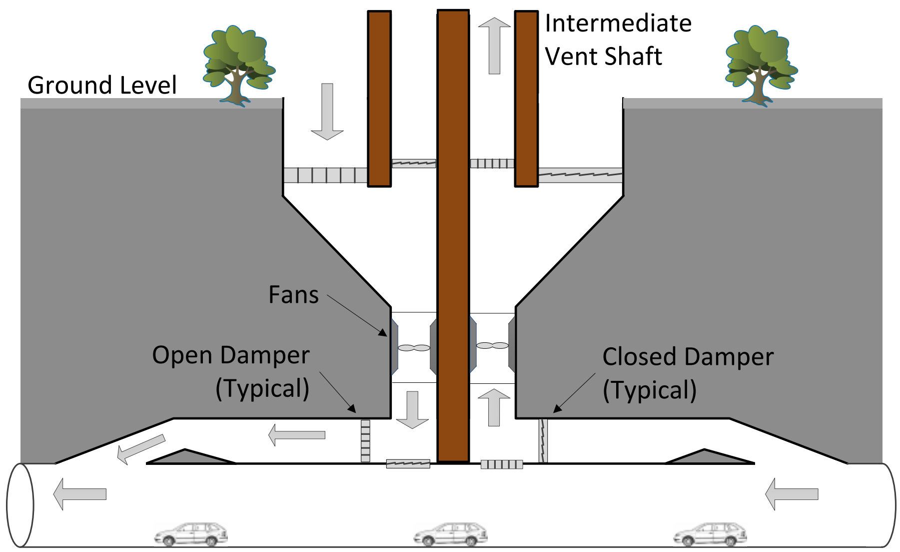


Figure 14: Example of Mid-Tunnel Ventilation with Saccardo Nozzles for Longitudinal Ventilation

Due to community and stakeholder concerns about intermediate shafts, alternative designs including a separate ventilation tunnel were designed. ILF Consultants proposed an innovative ventilation concept and design approach that eliminates both the intermediate ventilation shafts and the need for a separate ventilation tunnel.

Four ventilation concepts were considered and investigated for the freeway tunnel alternatives:

- Concept 1: Distributed smoke extraction with exhaust duct in invert
- Concept 2: Distributed smoke extraction with third bore as exhaust duct
- Concept 3: Midpoint smoke extraction
- Concept 4: Longitudinal ventilation, with no exhaust extraction system

After further modeling and investigation, the longitudinal ventilation concept is determined to best meet the requirements of this project.

If self-ventilation due to the piston effect of the vehicles does not result in a sufficiently large air exchange, jet fans are used to support the natural flow. This will typically be the case only for very slow-moving traffic.

Air filtering devices with a flow bypass for emergency operation will be installed in the portal buildings of the exit portals. They are designed to minimize the emission of vehicular pollutants from the tunnel in the portal areas.

5.4 Ventilation Design

Figure 13 shows a schematic drawing of the proposed freeway ventilation system. This drawing shows the two bores with two driving decks in each direction. Longitudinal flow is controlled with jet fans, which are installed in the cut and cover section of the tunnel. Both tunnels show a double deck and jet fans in the cut and cover section. Parallel to the traffic area, the exhaust duct is connected by dampers to the exhaust fans at the portals. The by-pass for air scrubbing is as indicated.

Besides eliminating the impact of intermediate vent shafts in the neighborhoods, this innovative ventilation concept also reduces the complexity and cost of the underground installation. The exhaust duct is efficiently incorporated in the lateral spaces of tunnel cross sections which are not useful for roadway area.

Jet fans are provided to control the longitudinal velocity of the air flow. These jet fans are located in the cut and cover sections where more space is available in the traffic area.

The inner section (tunnel boring machine (TBM) section) is planned without jet fans. In case of a fire, smoke can be extracted by dampers located every 300 feet. The fire detection system must be capable of locating the fire.

Smoke in the traffic area is extracted through the two open dampers next to the fire location into the exhaust duct by using exhaust fans spaced in the portal ventilation building.

To reduce environmental impact in the portal area, air scrubbers are included in the design of both portal ventilation buildings. This is possible by having a by-pass of the exhaust duct. Tunnel air is extracted close to the exit portal and passes the air scrubbers before it leaves the tunnel system through the stacks next to the interchanges.

On each deck a walkway separated by fire walls from the traffic area is shown in the tunnel configuration. Supply fans spaced in the portal ventilation building produces a higher pressure to prevent a smoke extraction in case of a fire by open an emergency exit.

The ventilation concept for normal operation is longitudinal ventilation using jet fans. In the case of a fire, the concept allows smoke extraction locally with automated exhaust dampers. Ventilated emergency walkways are provided along the tunnel. There are air scrubbers at the exit portals of both tunnels.

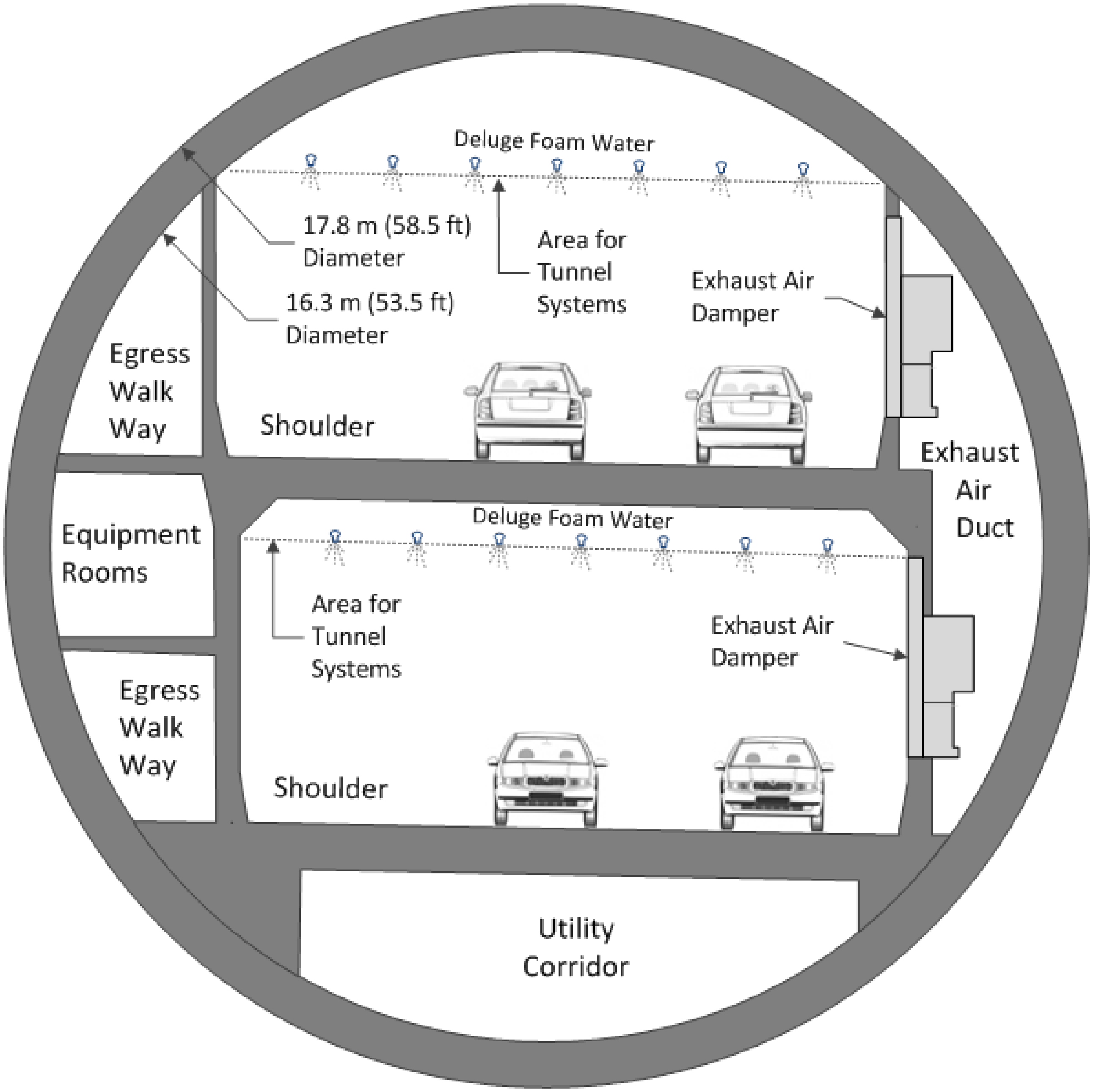


Figure 15: Tunnel Bore Cross Section

The OMC buildings are provided in the cut and cover sections near both portals located in-between the two tunnel tubes. They are equipped with two exhaust fans which allow extraction of smoke from both tunnels.

The exhaust fans are designed for a temperature resistance of 750°F (399°C) over two hours. Smoke is extracted by operating the exhaust fans at both buildings in combination with two open dampers downstream of the incident location.

Under normal operation, the tunnel air is “scrubbed” for air quality reasons, which reduces emissions at the ventilation shafts. The current design considers filters capable of greatly reducing particulate matter. The filters are capable of removing 90 – 95% of PM_{10} particles (10-µm-wide) and 80 - 85% of $PM_{2.5}$ particles (2.5-µm-wide). Typically, the piston effect produced by moving vehicles pushing air through the tunnels is sufficient to meet the tunnel air quality limits. This mode of operation is referred to as a self-ventilated tunnel situation. If the piston is diminished by lower traffic speeds, the jet fans near the portals buildings support the velocity in the tunnel in traffic direction. Close to the exit portal, tunnel air is extracted and air scrubbers scrub the tunnel air before leaving out of the ventilation stacks.

Under heavier traffic conditions, ventilation is mechanically assisted to keep the air quality in the tunnel within required limits for opacity, carbon monoxide, and nitrogen oxides. Used tunnel air is bypassed into the exhaust scrubbers near the portals. The ventilation system is modulated to respond to the measured CO levels within the tunnel. When CO emissions are controlled, other air contaminants are also maintained at acceptable levels.

A separate environmental investigation of the ventilation shaft exhaust and dispersion was subsequently performed by CH2M HILL to confirm that outside air quality will remain within acceptable limits.

In case of a fire, the ventilation system provides safe egress in the enclosed and pressurized walkways with emergency exits spaced every 183 m (600 feet) or less. Local smoke extraction occurs through controllable dampers opened adjacent to the fire location. Longitudinal flow is controlled with jet fans to maintain smoke-free zones upstream of the incident location.

During a fire emergency operation, two dampers next to the fire position open and the rest close. The exhaust fans in the portal ventilation buildings extract the smoke from the traffic area into the exhaust duct. Jet fans in the cut-and-cover section control the air velocity on both sides of the fire and produce a flow direction from each portal to the fire position to prevent smoke extraction in the traffic tube. In traffic direction critical velocity is produced in accordance to NFPA 502.

Supply fans in the portal ventilation buildings produce an overpressure in the walkways to prevent smoke from entering into the walkways when an emergency exit door is opened. This overpressure is limited to 50 Pa.

The ventilation system is designed to operate normally with one open vehicle cross passage with no consequences to the safety level of the walkways. If two vehicle cross passages are open at the same time, the walkway between the two open vehicle cross passages may not be adequately ventilated. Monitoring of the vehicle cross-passage doors can alert the tunnel operator to this alarm condition.

For more information about the ventilation design, see Appendix D.

5.5 Air Filtering

Preliminary dispersion models (which are not within the scope of this report) have shown that the concentration of pollutants does not exceed permissible values at the portal areas. However, as a precautionary measure to address concerns of increased concentrations of pollutants in the portal areas, all freeway options have an air scrubbing system at the exit portal of each tunnel. This air scrubbing system removes most of the particulate matter (PM) emissions and also addresses the noxious gases.

This section gives a general overview of air filtering technologies. Different pollutants require different techniques for their removal. Table 8-3 lists pollutants and cleaning methods relevant in a tunnel environment.

Table 6: Pollutants and Cleaning Methods Relevant in a Tunnel Environment

Pollutant	Scrubbing Method
Particulate Matter (PM)	electrostatic
NO_x	absorption, catalytic
CO	catalytic, combustion
CH	absorption, catalytic, combustion
SO_2	absorption, catalytic

Each OMC building extends from the tunnel level to above ground. The final exhaust air locations have not been determined yet. One possibility is to extend the exhaust duct from the south portal area to the I-10 / SR 710 interchange. For the north portal, one proposed design alternative is to incorporate the vent shaft into the architecture of the OMC building.

During an emergency event, preventing smoke from entering the emergency walkway area is of paramount importance. To keep the walkway smoke-free, supply fans, located in the OMC buildings, will create positive pressure in the walkways. This excess pressure causes fresh air to flow from the walkway into the traffic area.

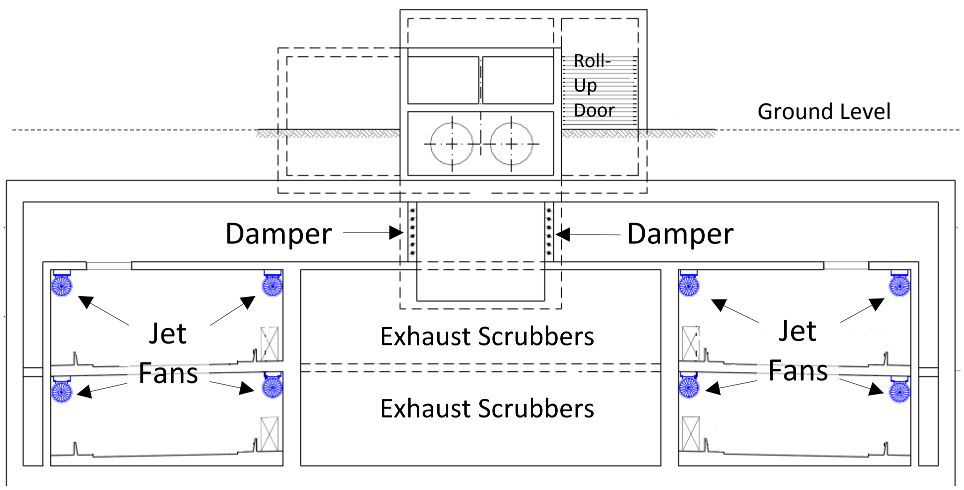


Figure 16: Cross Section of Cut and Cover of the North Portal OMC Building

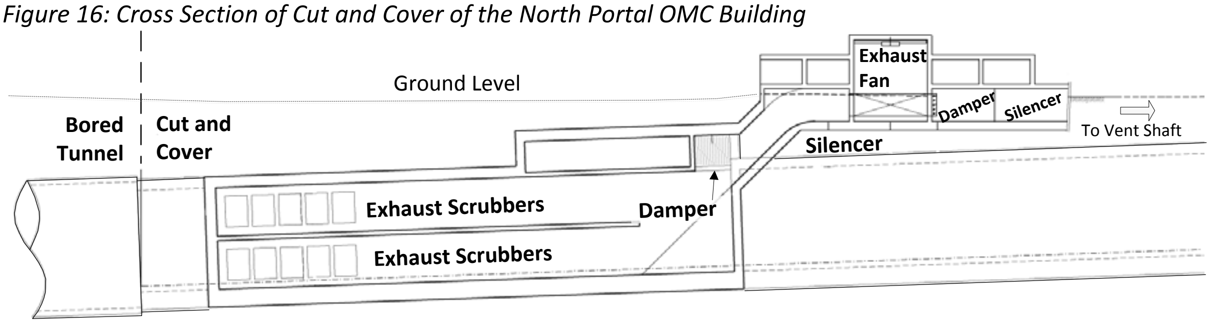


Figure 17: Longitudinal Section of the North Portal OMC Building

Non-public areas of the tunnel such as equipment room areas, lower utility corridor, and other ancillary spaces must comply with the ventilation requirements as described by U.S. Occupational, Safety, and Health Administration (OSHA).

5.5.1 Electrostatic Filters

Electrostatic filters are used to clean tunnel air of PM. PM can be dispersed over a wide area near the tunnel portals. Of particular attention are the PM-10 particles, which include a weighted sum of all particles with a diameter of less than 10 µm

In road traffic, PM stems from incomplete combustion, particularly in diesel engines, and if not filtered, from tire abrasion and from dust transported with the vehicles and deposited in the tunnel. The first measure to reduce PM emission from tunnel portals is to ensure that the tunnel is regularly cleaned with high-pressure water. The second measure is the installation and use of electrostatic air filters at the tunnel portals, which can clean the exhaust air at the corresponding portal continuously. There are several companies that offer technical systems particularly suited for the tunnel environment.

Electrostatic filters remove particulate matter, typically in a three-step approach (see Figure 18):

1. Protective grid for large particles
2. Ionization of exhaust air and subsequent segregation in electrically charged collectors
3. Electrostatically charged filter medium

Depending on the requirements, these steps can be repeated within the filter device to improve the efficiency of the filtering. The ionizer and the electrostatic filter cell are automatically wet cleaned with connected water treatment. The dry dust from the filter media is automatically collected into dust bins and must be disposed of regularly.

Figure 18: Schematic Drawing of the ECCONOxCAT Filter (source: http://www.aigner.at)

5.5.2 Catalytic Filters / Adsorption

Products of incomplete combustion, such as CO, CH, NO_x, SNO_x), can be reduced catalytically or by adsorption.

At the present time there are no technologies available, such as catalytic converters, able to filter gaseous emissions such as oxides of nitrogen and hydrocarbons from large volumes of exhaust.

Catalyst materials include ceramics with platinum or palladium coating. This method requires frequent regeneration, which is why it can also be considered adsorption.

Adsorbents include potassium (K+) or calcium (Ca+) in combination with the hydroxide radical (OH–) and active charcoal. The costs for (regenerative) catalytic methods and for adsorbing filters are generally comparably high as the active material needs replacement and disposal.

6. Limitations

This Preliminary Systems Report has been prepared for the exclusive use of Caltrans and Metro for specific application to the SR 710 North Study in Los Angeles County, California. The report has been prepared in accordance with generally accepted systems and fire/ life safety engineering practices. No other warranty express or implied, is made.

This report is a compilation of memoranda and studies performed as part of the CH2M Hill study and those memoranda are reproduced and referenced as appendices herein. This report serves as the comprehensive summary of that work product and supersedes all earlier reports and memoranda.

The information contained in this report is based on U.S. and international guidelines and standards combined as applied to the Caltrans and LA Metro design criteria. Meetings with the California Fire Marshal provided further guidance. These inputs have constituted the basis of the systems design along with, previous and current field investigations and studies within the SR 710 North Study Area.

The information contained in the appendices provide a uniform basis for the analysis and design. The information can be used except where specific circumstances make such application impractical. These documents are intended to be a living document that will be updated/revised as necessary.

The information serve as guideline and do not substitute for engineering judgment and sound engineering practice. Specific exceptions may apply in special cases. The Engineers are responsible for identifying any necessary departure from the information contained in this document.

In the event that any change in the nature, design, or location of the SR 710 North Study Alternatives occurs, conclusions and recommendations of this report should not be considered valid unless such changes are reviewed, and the conclusions of this report are modified or verified in writing by CH2M HILL team. CH2M HILL or ILF Consultants are not responsible for any claims, damages, or liability associated with the reinterpretation or reuse of the data in this report by others.

SR 710 NORTH STUDY

This page intentionally left blank.

7. References

Aigner. 2012. Website: www.aigner.at.

AASHTO LRFD Bridge Design Specifications, 4th Edition. 2007. A publication by the American Association of State Highway and Transportation Officials.

California Department of Motor Vehicles. 2012. Vehicle Code. Section 35550-35558.

California Department of Transportation (Caltrans). May 7, 2012. Highway Design Manual, 6th Edition, State of California, Sacramento, CA.

CH2M HILL. 2010. Final Geotechnical Summary Report. SR 710 Tunnel Technical Study. Los Angeles County, California. Prepared for the California Department of Transportation, April 2010.

CH2M HILL. 2012a. Email from J. Emerson. 07/30/12. Subject: meeting.

CH2M HILL. 2012b. Future Systems Performance Report. In Progress. Prepared for the Los Angeles County Metropolitan Transportation Authority.

CivilTech. 2011. Shoring Suite, Version 8.1.2h.

Clough, G.W., and T.D. O'Rourke. 1990. Construction induced movements of in-situ walls. In *Proceedings, Design and Performance of Earth Retaining Structures*. New York City. 439–470.

Department of Justice. 1991. ADA Standards for Accessible Design.

Earth Mechanics Inc. (EMI). 2005. Preliminary Geological and Geotechnical Characterization for the Proposed 710 Freeway Tunnels. A report prepared for the Tunnel Advisory Panel, Metropolitan Transportation Authority, Los Angeles, CA.

EMFAC2011, www.arb.ca.gov/msei/modeling.htm, January, 2014.

Los Angeles County Metropolitan Transportation Authority (Metro). 2010. Metro Rail Design Criteria, Section 4 / Guideway and Trackwork.

National Fire Protection Association (NFPA). 2010. Standard for Fixed Guideway Transit and Passenger Rail Systems, NFPA 130, Quincy, MA.

National Fire Protection Association (NFPA). 2011. Standard for Road Tunnels, Bridges and Other Limited Access Highways, NFPA 502, Quincy, MA.

Peck, R.B. 1969. Deep excavations and tunneling in soft ground—State of the art report. In *Proceedings 7th International Conference on Soil Mechanics and Foundation Engineering*. Mexico City. 225–290.

PIARC. 2012. Road Tunnels: Vehicle Emissions and Air Demand for Ventilation Road Tunnels: PIARC Technical Committee C4. Road Tunnels Operation. Report No. 2012R05EN. PIARC: La Défense, 2012.

PLAXIS BV. 2010. PLAXIS 2D2010. A Program for Finite Element Geomechanical Analysis. Delft, The Netherlands.

Ranken, R.E., J. Ghaboussi, and A.J. Hendron. 1978. Analysis of Ground-Liner Interactions for Tunnels. Report No. UMTA-IL-06-0043-78-3, US Department of Transportation, Washington DC.

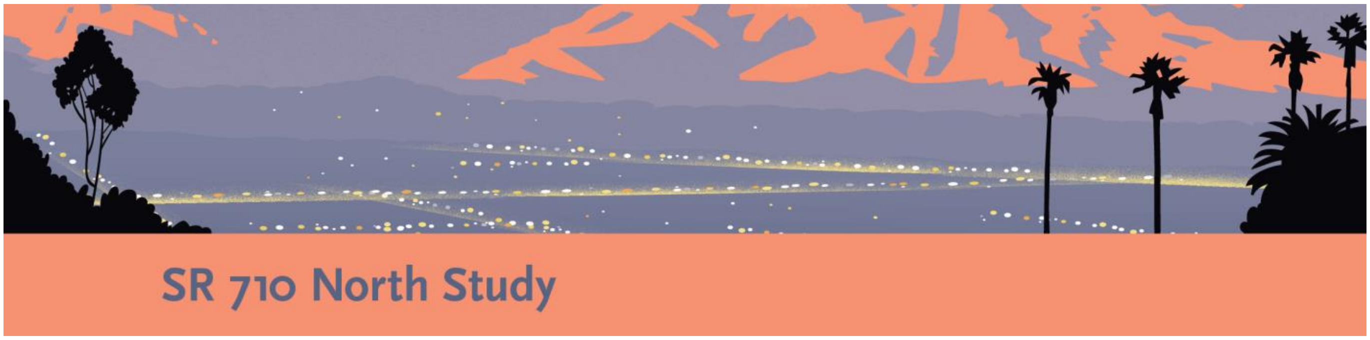
Schurch, M., 2006. Small But Important-Gaskets for Tunnel Segments, in International Symposium on Underground Excavation and Tunnelling, February 2006, Bangkok, Thailand, pp. 239-248.

Smirnoff, T.P., A. Stirbys, and A. Elioff. 1997. Comparison of performance of soil mix wall and conventional bracing system for excavations in alluvium. In *Rapid Excavation and Tunneling Conference Proceedings 1997*, pp. 59-71.

Tunnels and Tunnelling International. 2006. 'Mega' Performance for Madrid's M30. 8 September, 2006.

SR 710 NORTH STUDY

This page intentionally left blank.



Systems Project Report for the Freeway Tunnel Alternative

Appendix A - Guidelines and Standards

Prepared for

Metro

Los Angeles County
Metropolitan Transportation Authority

4/24/2014

CH2MHILL®

1000 Wilshire Boulevard
Suite 2100
Los Angeles, CA 90017

American Association of State Highway and Transportation Officials (AASHTO)

- Highway Design and Operational Practices Related to Highway Safety.
- Roadside Design Guide, 4th Edition
- Roadway Lighting Design Guide
- Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals
- National Transportation Communications for ITS Protocol (NTCIP)

American National Standard Institute/Illuminating Engineering Society of North America (ANSI/IESNA)

- ANSI/IESNA RP-22-2005: Recommended Practice for Tunnel Lighting
- ANSI/IESNA RP-8-2000: Recommended Practice for Roadway Lighting
- ANSI C2: National Electrical Safety Code
- IESNA RP-19: Roadway Sign Lighting
- IESNA: Lighting Handbook
- IESNA LM-50-99: Photometric Measurement of Roadway Lighting Installations
- IESNA LM-71-96: Photometric Measurement of Tunnel Lighting Installation
- 80: Guide for Safety in AC Substation Grounding
- 81: Guide for Measuring Earth Resistivity

State of California

- Vehicle Code, Section 35550-35558
- California Air Resources Board, EMFAC2011
- California Building Code (CBC)
- California Fire Code
- California Electrical Code

Caltrans, Standard Specifications

- Caltrans, Signal, Lighting, and Electrical Systems Design Guide
- Caltrans, Manual on Uniform Traffic Control Devices
- Caltrans, Highway Design Manual

Federal Highway Administration (FHWA)

- Manual on Uniform Traffic Control Devices (MUTCD)
- Revised Guidelines for the Control of Carbon Monoxide (CO) Levels in Tunnels, March 31, 1989
- Traffic Control Systems Handbook

International Commission on Illumination

- CIE 88:2004 Guide for the Lighting of Road Tunnels and Underpasses

Institute of Electrical and Electronics Engineers (IEEE)

- National Electrical Safety Code (NESC)
- Standard 730: Software Quality Assurance Plan
- Standard 830: Recommended Practice for Software Requirements
- Standard 1012: Software Verification and Validation
- Standard 1016: Recommended Practice for Software Design Descriptions

Institute of Transportation Engineers (ITE)

- Equipment Materials Standards: Vehicle Traffic Control Signal Heads (VTCSH)
- Traffic Engineering Handbook
- Highway Safety Manual
- Traffic Control Devices Handbook

City and County of Los Angeles

- Los Angeles City Fire Code
- Los Angeles County Building Code
- Los Angeles County Fire Code

National Cooperative Highway Research Program (NCHRP)

- Report 525 Volume 12: Making Transportation Tunnels Safe and Secure

National Fire Protection Association

- Fire Protection Handbook, 20th Edition
- NFPA 1: Fire Code
- NFPA 10: Standard for Portable Fire Extinguishers
- NFPA 11: Standard for Low- Medium- and High-Expansion Foam
- NFPA 13: Standard for Installation of Sprinkler Systems
- NFPA 14: Standard for the Installation of Standpipe and Hose Systems
- NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection
- NFPA 16: Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems
- NFPA 17: Standard for Dry Chemical Extinguishing Systems
- NFPA 18: Standard on Wetting Agents

- NFPA 20: Standard for the Installation of Stationary Pumps for Fire Protection
- NFPA 22: Standard for Water Tanks for Private Fire Protection
- NFPA 24: Standard for the Installation of Private Fire Service Mains and Their Appurtenances
- NFPA 25: Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems
- NFPA 30: Flammable and Combustible Liquid Code
- NFPA 70: National Electrical Code
- NFPA 72: National Fire Alarm and Signaling Code
- NFPA 80: Standard for Fire Doors and Other Opening Protectives
- NFPA 90A: Installation of Air Conditioning and Ventilating Systems
- NFPA 92: Standard for Smoke Control Systems
- NFPA 101: Life Safety Code
- NFPA 110: Standard for Emergency and Standby Power Systems
- NFPA 111: Standard on Stored Electrical Energy Emergency and Standby Power Systems
- NFPA 220: Types of Building Construction
- NFPA 241: Safeguarding Construction, Alternation, and Demolition Operations
- NFPA 251: Standard Methods of Tests of Fire Endurance of Building Construction and Materials
- NFPA 262: Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces
- NFPA 502: Standard for Road Tunnels, Bridges and Other Limited Access Highways
- NFPA 750: Standard on Water Mist Fire Protection Systems
- NFPA 1561: Standard on Emergency Services Incident Management System
- NFPA 1600: Standard on Disaster/Emergency Management and Business Continuity Programs
- NFPA 1963: Standard for Fire Hose Connections
- NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems

National Institute of Standards and Technology

- SP 800-82: Guide to Industrial Control Systems (ICS) Security

National Electrical Manufacturers Association (NEMA)

- Standards Publications/No. 250, Enclosures for Electrical Equipment (1,000 Volts Maximum)

Occupational Safety & Health Administration (OSHA)

- OSHA Technical Manual (OTM) Section III: Chapter 3, Ventilation Investigation

Swiss Federal Roads Office (ASTRA)

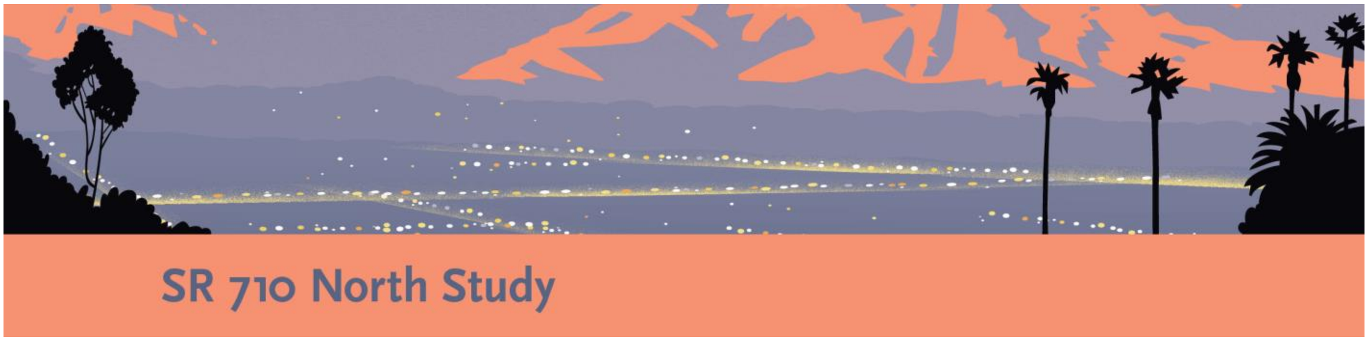
- Ventilation of road tunnels. 13001. V2.01 (2008)

Telecommunications Industry Association/Electronic Industries Alliance (TIA/EIA)

- FOTP 455-171A: Attentuation by Substitution Measurements for Short Length Multimode Graded Index and Single Mode Optical Fiber Cable Assemblies
- FOTP 455-61A: Measurement of Fiber or Cable Attenuation Using an Optical Time-domain Reflectometer (OTDR)
- Electronic Industries Alliance Standards and Technical Problems

Underwriters Laboratory

- 1971: Signaling Devices for the Hearing Impaired



TECHNICAL MEMORANDUM

Appendix B - OMC STAFFING AND PROVISIONS

PREPARED FOR: METRO

COPY TO: CH2MHill

PREPARED BY: CH2M Hill team (ILF Consultants, Inc.)

DATE: May 7, 2013

PROJECT NUMBER: 428908

In the Fire Marshal meeting on March 26, 2013, there was discussion about staffing and facility requirements for the OMC. It was decided in that meeting that first responders must be located at the OMC at both portals. An action item from this discussion was to research the staffing and facility provisions for similar highway tunnels in the United States and Europe. This memo responds to this action item.

Co-Location of First Responders

A list of all U.S. tunnels longer than 3,000 feet was reviewed. This list is provided in Table 2 at the end of this memo. None of these tunnels were found to include co-located first responders. Apparently, the SR 710 tunnel is the first U.S. tunnel with this provision.

Most European tunnels also do not have co-located firefighters or emergency staff including the 8.7 mile Arlberg Road Tunnel. Two European tunnels with co-located first responders were identified, the Mont Blanc Tunnel and Frèjus Road Tunnel.

Mont Blanc Tunnel (France/Italy)

In the 7.2 mile Mont Blanc Tunnel there are 11 firefighters on duty 24 hours a day. These professionals are highly qualified for firefighting intervention in a confined space. They are positioned in three locations: at each tunnel portal and at a tunnel midpoint.

Figure 1 Mont Blanc Tunnel Fire Post

Each position is provisioned with equipment and vehicles specifically designed for tunnel fire fighting. The portal locations include small emergency medical centers. Firefighters share common areas with tunnel operations staff and work in close coordination with them. (The size of first responder areas was not readily available for this memo.)

In addition to the fire fighters, there is a five-person traffic safety team and a six-person traffic safety assistant team on duty for managing traffic during incidents and fire emergencies. In the event of an incident, the safety team is responsible for initial action on the ground in coordination with the first responders. They are also in charge of escorts for abnormal loads. The safety assistants are mobilized to receive public emergency services and for tunnel evacuation. The assistants also manage checks on the heavy vehicles before these are permitted to enter the tunnel.

Total staffing requirements for the firefighting and traffic safety group is 72 persons. Total staffing for all five tunnel maintenance and operations groups is reported to be:

Mont Blanc Tunnel Staffing Groups	# of Persons
Management Functional Services	19
Administrative and	11
Customers and Toll	43
Safety and Traffic	72
Technical and Computing	49

Frèjus Road Tunnel (France/Italy)

In 2005, the 8.1 mile Frèjus Road Tunnel was upgraded with four emergency stations. Inside the tunnel at the 1/3 and 2/3 midpoints, there are emergency stations staffed with two safety officers and a fire-fighting vehicle. At the portals there are full fire-fighting teams. The objective of the interior stations is to reduce the intervention times in the event of an incident and to assist the public with evacuation as quickly as possible.

Total staffing for all traffic and fire control is reported to be approximately 100 persons.

(Sizing of these first responder facilities was also not readily available for this memo.)

Figure 2 Frèjus Road Tunnel Emergency Vehicle

OMC Control Room Requirements

> Fire Protection Handbook, Section 21, Chapter 11: *A full-time attended control room should be available for any road tunnel facility in which safe passage necessitates fixed fire-fighting system protection. Therefore, consideration should be given to human interaction in the system control and activation design to minimize false alarms and accidental discharges.*

Comparable U.S. tunnels such as Caldecott, Devil's Slide, and Doyle Drive include on-site OMC buildings with monitoring control rooms that fulfill Central Supervising Station (CSS) requirements. As specified in NFPA 502, the CSS must be redundant, so there is an OMC at both portals.

Austrian tunnels of similar length provide control rooms at both portals, but these are only manned for maintenance or in an emergency. Regional control centers are continuously staffed that monitor several tunnels. This strategy is also used for the two I-90 Tunnels in Washington State. The control room of either I-90 tunnel is capable of serving as the CSS for the other tunnel. However, neither of these control rooms is normally staffed by an operator. Monitoring of both tunnels is provided from the WSDOT regional headquarters approximately 14 miles away.

International standard ISO 11064 defines standards for the ergonomic design of control centers. Control room layout is found in Part 3 of ISO 11064. This standard aims to provide general principles of ergonomic design appropriate to a range of industries, not just highway tunnels.

Highway tunnel control rooms are customarily provisioned for 24/7 staffing with at least two operator workstations and one supervisor workstation. Because CCTV is a prominent aspect of the safety systems, a video wall is provided in modern control centers. A sketch of a preliminary, proposed control room layout for the SR 710 OMC control room is shown in Figure .

Figure 3 Operator and Supervisor Workstations

Figure 4 Video Wall

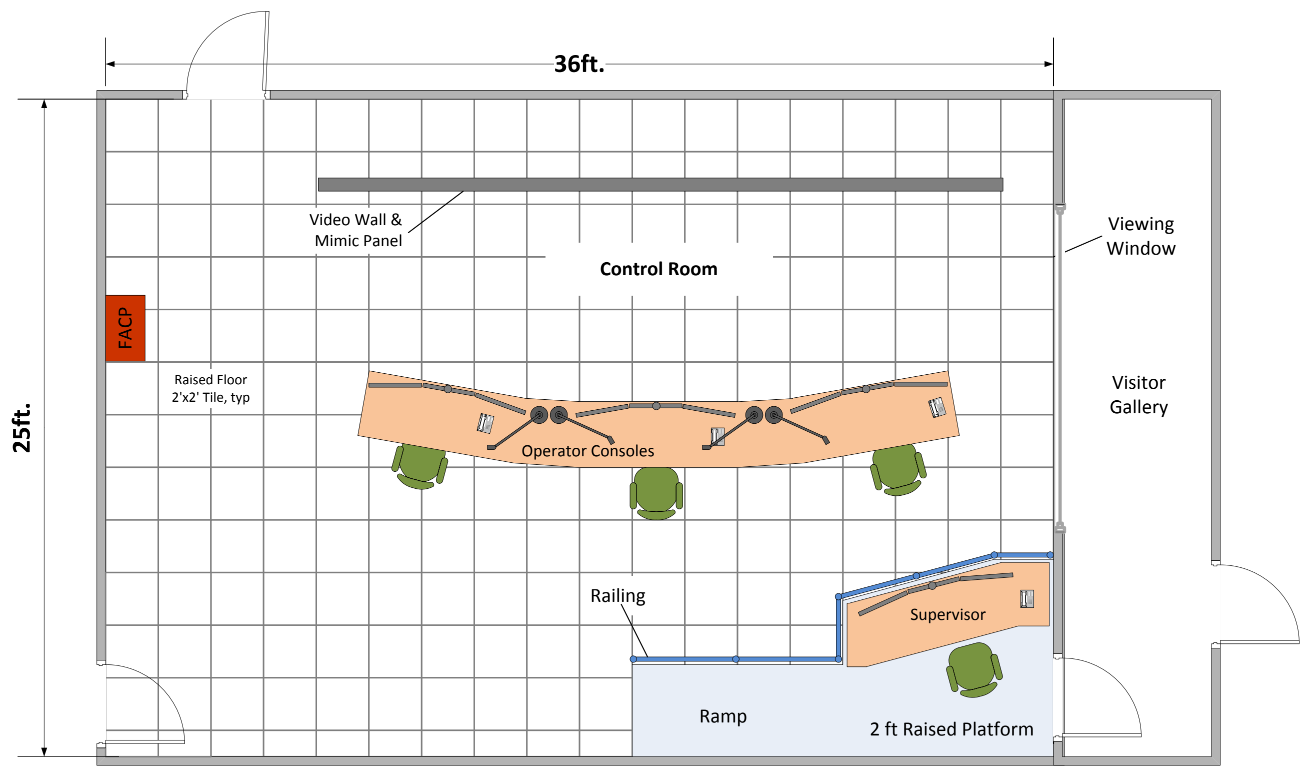


Figure 5 Preliminary SR 710 Control Room Layout

In addition to the control room proper, other related rooms provide supporting functions. These are listed in the Table 1 below with proposed minimum size requirements. These suggested minimum sizes are based in part on Austrian National Roadway Association (ASFiNAG) standards.

Table 1: Control Room and Associated Room Sizes

Room	Description	Minimum Size [ft2]	Minimum Height [ft]
Control Room	Tunnel Central Supervising Station	900	16
Computer Equipment Room	Adjacent to the Control Room with racks/cabinets with the uninterruptible power supply, servers, network, video, and other electronic equipment	650	10
Crisis Management Room	Attached to the control room with a window to enable the crisis management team to view the control room video wall	350	10
Visitor Gallery	General public visitor viewing area		

As mentioned earlier, the square footage for the first-responder areas in the European tunnel examples was not available. A reasonable first estimate is that these first-responder areas are comparable to a small fire station. Based on this assumption, a local fire station in Long Beach was reviewed. At 3,000 square feet, it provides storage and living quarters for five firefighters. In addition, space for two vehicles are needed at each portal, consistent with the Long Beach Fire Station and the two tunnels in Europe.

Tunnel	Length (ft)	Opened	State	Road
Ted Williams / I90 Extension	13780	1995 2003	MA	I-90
Anton Anderson Memorial	13725	2000	AK	
Brooklyn Battery	9116	1950	NY	I-478
Eisenhower Memorial	8959	1979	CO	I-70
Holland	8555	1927	NY-NJ	I-78
Lincoln Center	8214	1937	NY	495
Lincoln South	8004	1957	NY	495
Thomas O'Neill Jr.	7873	2003	MA	I-93
Baltimore Harbour	7650	1957	MD	I-895
Hampton roads	7479		VA	I-64
Lincoln North	7483	1945	NY	495
Fort Mc Henry	7164	1995	MD	I-95
Wacker Dr.	6643		IL	
Queens Midtown	6413	1940	NY	495
Allegheny	6069	1940 1966	PA	I-76
Thimble Shoal	5737	1964	VA	US13
Liberty	5688		PA	I-579
Sumner	5659		MA	1A
Zion	5613		UT	9
Chesapeake Channel	5423	1999	VA	US13
East River Mountain	5400	1974	VA - WV	I-77
Tuscarora Mountain	5324	1940	PA	I-76
Trans Koolau (Tetsuo Harano)	5163		HI	H3
Detroit - Windsor	5131	1930	MI	401
Callahan	5068		MA	1A
Monitor Merrimac Memorial	4799		VA	I-664
Kittatinny Mountain	4727	1940	PA	I-76
Lehigh	4461	1940	PA	I-76
Blue Mountain	4340	1940	PA	I-76
Cumberland Gap	4258		TN - KY	US25E
Wavona	4232		CA	RT41
Big Walker Mountain	4228	1972	VA	I-77
Squirrel Hill	4225	1953	PA	I-376
Midtown (2nd Norfolk Portsmouth)	4192	1962	VA	US58
Devil’s Slide	3999		MT	US1
Hanging Lake	3999		CO	I-70
Downtown (1st Norfolk Portsmouth)	3812	1987	VA	I-264
Washburn	3763		TX	
Lake Shore	3690		IL	
Wabash	3658	1904	PA	
Caldecott 1 & 2	3615	1982	CA	CA24
Fort Pitt	3599	1960	PA	I-279
Posey	3546	1928	CA	US24
I 95 - Mall	3398		DC	
Bankhead	3389	1941	AL	US98
Caldecott 3	3369	1982	CA	CA24
Webster	3349	1928	CA	US24
Mt. Baker	3300		WA	I-90
Michigan Av.	3297		IL	

Technical Memoranda References

http://www.lotsberg.net/data/USA/list.html Road Tunnels in United States > 1000 m

http://www.atmb.com/atmb/en/tunnel/22/tunnel-safety.html Mont Blanc Tunnel

http://www.tunnelmb.net/v3.0/gb/societe_gb.asp#lasociete Mont Blanc Tunnel

http://www.sftrf.fr/web/guest/tunnel/securiteintro Frèjus Road Tunnel

"Findings of the International Road Tunnel Fire Detection Research Project" Fire Technology, 46, 697–718, 9/5/2010

TECHNICAL MEMORANDUM

Appendix C - Lighting System: Lamp Type Selection

PREPARED FOR: Metro

PREPARED BY: CH2M Hill team (ILF Consultants, Inc.)

DATE: April 22, 2013

PROJECT NUMBER: 428908

An important consideration for the lighting design is the selection of the lamp types. According to NFPA 502 and ANSI/IES RP 22, different lamp types are acceptable in road tunnels. However, the lighting system design must consider economy and safety. The selection of lamp type is fundamental to both. The lamp types under consideration are:

- LED (light emitting diode)
- HPS (high pressure sodium)
- Fluorescent

ANSI/IES RP 22 defines different zones for the tunnel lighting system (threshold, transition, interior, and exit zone). These are shown in **Error! Reference source not found.**.

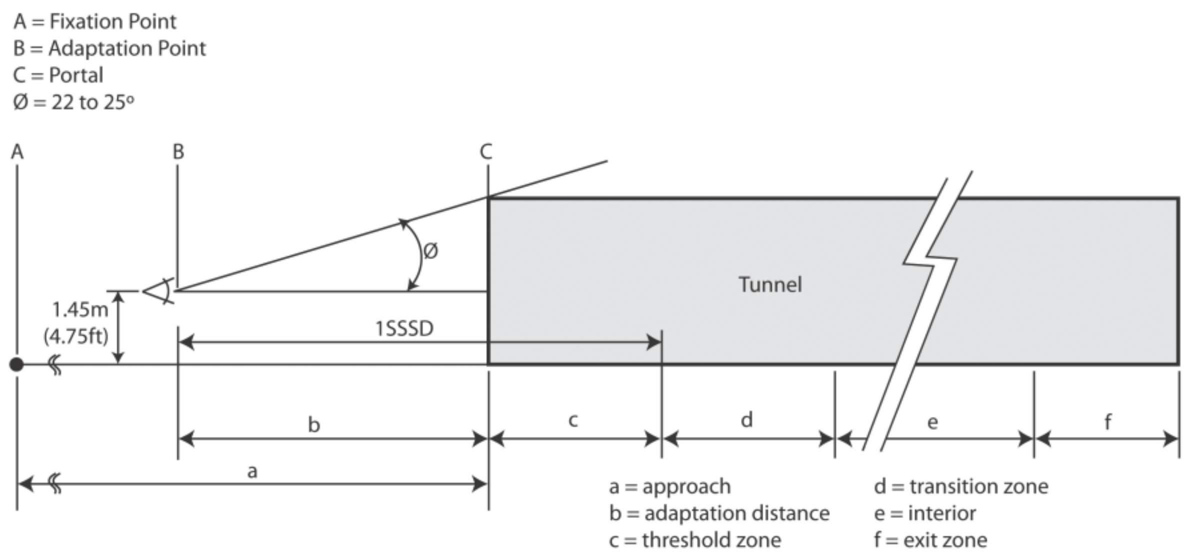


Figure 1 The Primary External and Internal Areas Associated With and Affected By Tunnel Lighting Design.

Interior and Exit Zones

From a safety point of view, several factors must be considered:

- Flicker effect: Distracting stroboscopic flicker sensations can be experienced by motorists driving through variations in the luminance on the roadway due to the spacing between light fixtures. This effect can be mitigated in the design by fixture placement.
- CRI (Color Rendering Index): CRI describes how well a light source reproduces colors faithfully in comparison to natural light. In the Tunnel Workshop on March 26, 2013, the fire marshal emphasized the need for responders to distinguish colors in the tunnel.
- Restrike time: This is the time delay for the lamp to turn on again after a power interruption.

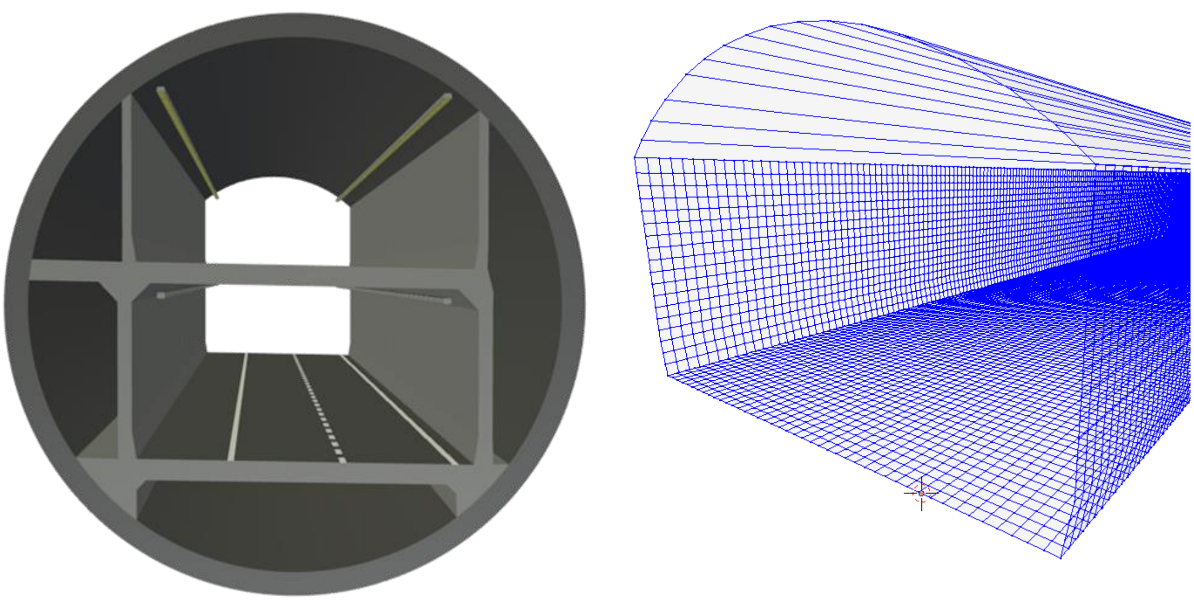
Fluorescent and LED lamps are clearly superior to HPS for all three factors: possibilities for close fixture placement (to minimize the flicker effect), higher CRI, and instant restrike. A summary of these factors is shown in Table 1.

Lamp Type	Flicker Effect	CRI	Restrike Time
LED	Minimized	Best	Instant
HPS	Poor	Poor	2 – 10 minutes
Fluorescent	Minimized	Good	Instant

Table 1: Safety Factors

To determine the projected operating costs, the energy consumption of both fluorescent and LED were computed. The 3D model of the current tunnel configuration, the 3D calculation mesh, and the results are shown in the following figures. The lighting calculation results in the number of lamps and spacing between light fixtures to meet ANSI/IES RP 22 and NFPA 502 requirements.

Figure 2: Current Tunnel Configuration and 3D Mesh for Calculation



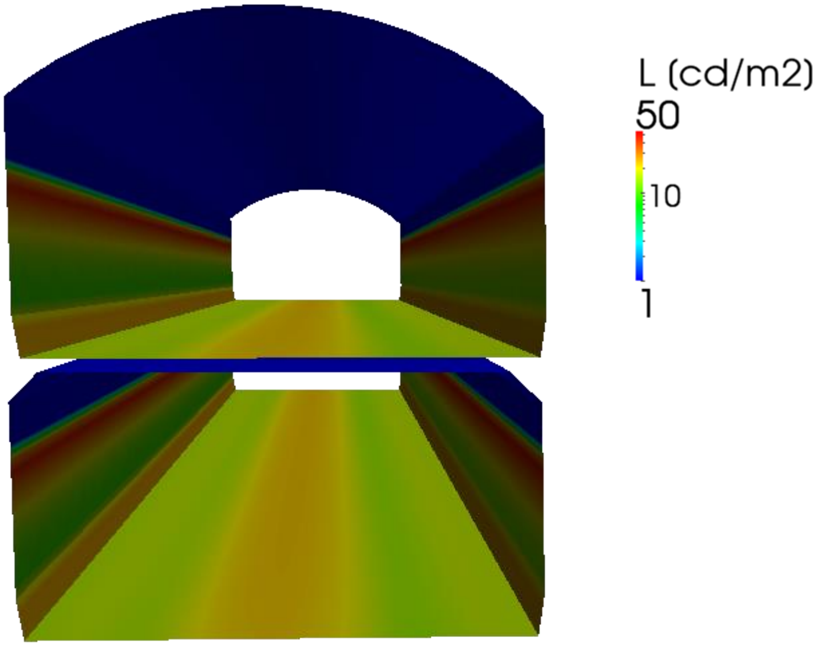


Figure 3: Result of the Lighting Calculation

The results show that the energy consumption of LED lamps in the interior zone is approximately 3,000,000 kWh/year less than fluorescent lamps for the freeway tunnel alternative. This is a reduction of approximately 25 - 30%. LED lamps have a higher initial investment, but a longer lifetime, lower maintenance costs, and higher efficacy (Lumens/W) justify the investment. The amortization time is estimated to be approximately five years.

Threshold and Transition Zones

Threshold and Transition zones require very high luminance during the day but are not required at night. LED can provide nighttime lighting in these zones. During the day the lamps must have a high luminous intensity and high efficacy (lumens/Watt). Flicker effect can be ignored in the threshold and transition zones, because the duration of the flicker is less than 20 seconds and that has minimal effect on motorists as described in ANSI/IES RP 22.

Summary

For the interior and exit zones LED lamps are preferable for their superior safety and overall economy.

For the threshold and transition zones, LED lamps are also preferable with the addition of HPS lamps for the high luminance needed during the day.

Technical Memoranda References

ANSI/IES RP 22-11

NFPA 502

Appendix D - Dimensioning of the Ventilation System for the Freeway Tunnel Alternative

Prepared for

Metro

Los Angeles County
Metropolitan Transportation Authority

4/24/2014

CH2MHILL®

1000 Wilshire Boulevard
Suite 2100
Los Angeles, CA 90017

Contents

Tables

Figures

Introduction

This report summarizes the preliminary design of the ventilation system for the single-bore and dual-bore freeway alternative. The ventilation system is designed for normal operation and for proper operation in case of an emergency. Each tunnel tube is approximately 58.5 ft in diameter and 4.9 mi long. Figure 1-1 shows the tunnel axis in the project area.

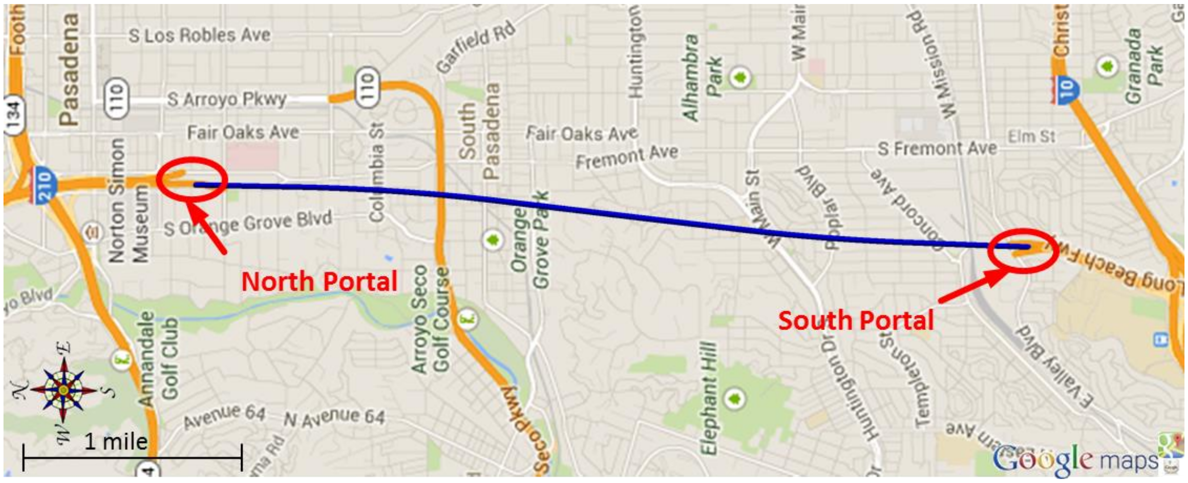


Figure 1-1: Plan View of the Tunnel Axis

The dual-bore variant has two side-by-side tunnels (one northbound and one southbound), with two levels and two lanes of unidirectional traffic and shoulder per level for a total of four lanes per tunnel.

The ventilation system of both variants consists of a continuous exhaust air duct with controllable dampers every approximately 300 ft. Redundant exhaust air fans are located at both OMC buildings. Jet fans are located in the Cut & Cover sections to influence the longitudinal air flow and to overcome meteorological pressure differences. Supply air fans are used at both OMC buildings to produce an overpressure in the walkway of the affected deck in case of an emergency. This overpressure causes fresh air to flow from the walkway into the traffic area. Local smoke extraction will happen via controllable dampers opened adjacent to the fire location. Longitudinal flow will be controlled with jet fans to maintain smoke-free zones upstream of the incident location.

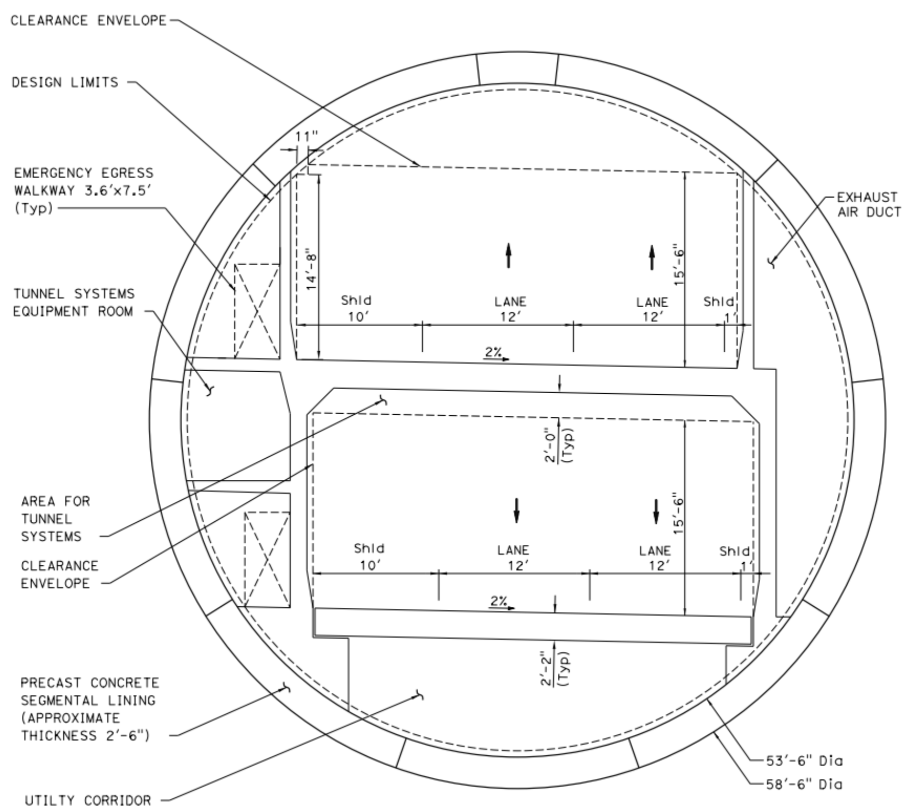
The ventilation concept for normal operation is longitudinal ventilation using jet fans. Closed to the exit portal the contaminated air is sucked with the exhaust air fans through the air scrubbers located in the OMC building. Under normal operation, the tunnel air will be “scrubbed” for air quality reasons, thereby reducing emissions at the ventilation shafts. The current design considers filters capable of greatly reducing particulate matter. The filters are capable of removing 90 – 95% of PM_{10} particles and 80 - 85% of $PM_{2.5}$ particles.

Fundamentals

2.1 Geometry

2.1.1 Cross Section of the Single Bore Tunnel

Figure 2-1 shows the cross section of the single bore alternative. On one level the vehicles will drive southbound while the vehicle on the other level will drive northbound.



TYPICAL SECTION

Figure 2-1: Cross Section for the Single Bore Alternative

2.1.2 Cross Section of the Dual Bore Tunnel

The cross section of the dual bore alternative is illustrated in Figure 2-2. In the left bore of the figure the vehicles will drive southbound while the vehicles in the right tube will drive northbound.

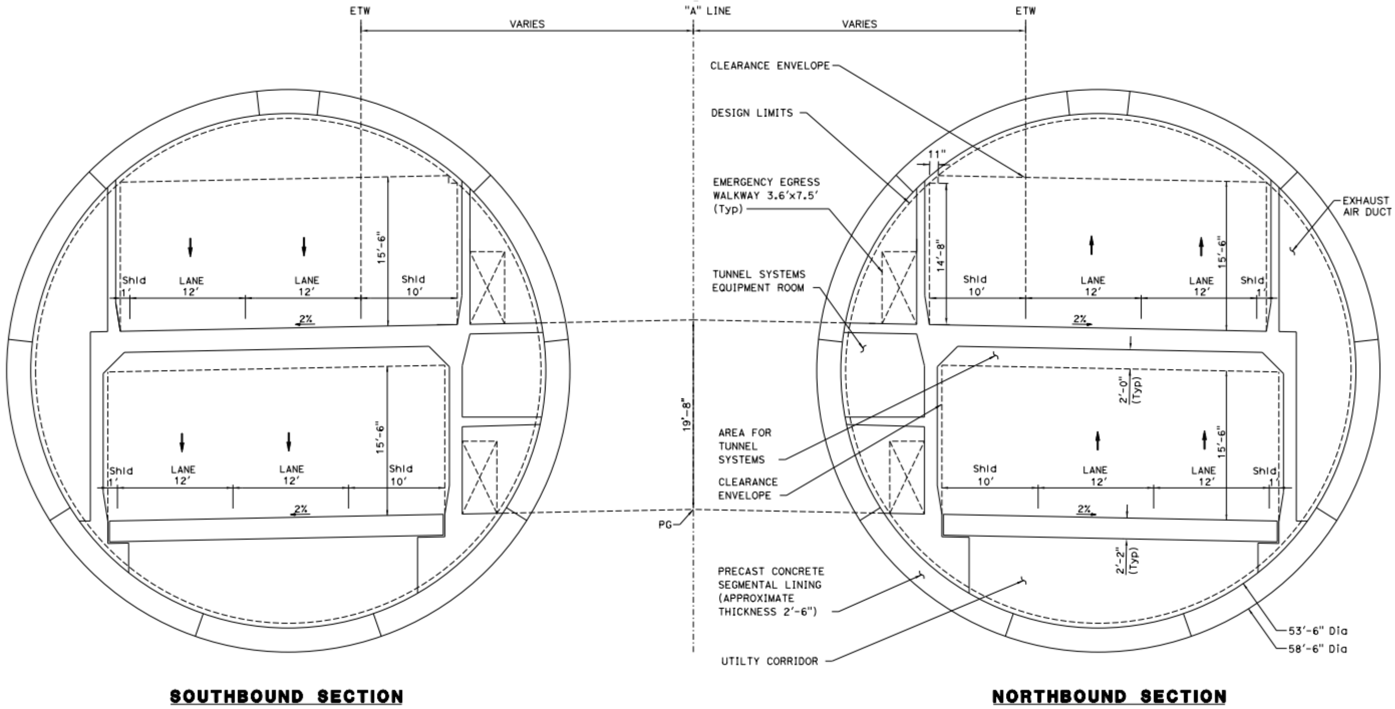


Figure 2-2: Cross Section for the Dual Bore Alternative

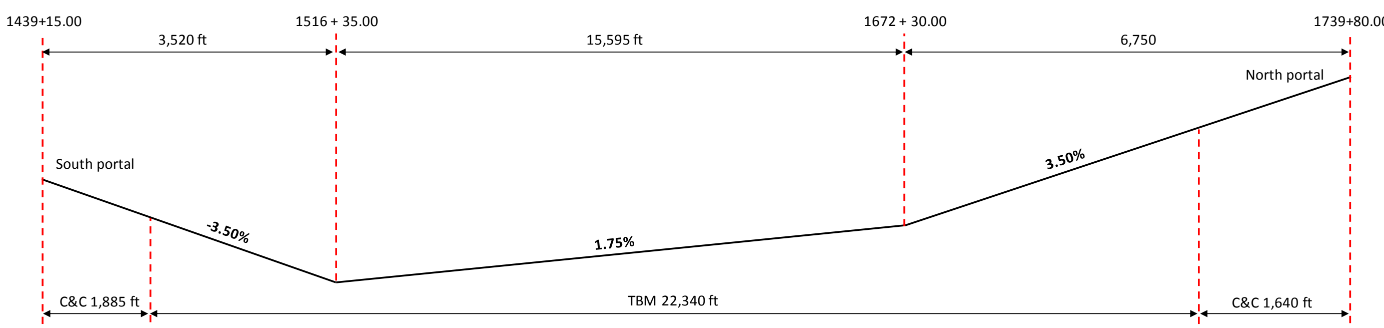


Figure 2-3: Longitudinal Section, North-Bound Lower Deck

Table 2-1: Dual-Bore North Bound

Geometrical Data			
Lower Deck		**Upper Deck**	
Length [ft]	25865	Length [ft]	24858.7
South portal [ft]	1439+15.00	South portal [ft]	1446+70.00
North portal [ft]	1739+80.00	North portal [ft]	1737+28.70
Altitude of south portal [ft a.s.l.]	379.6	Altitude of south portal [ft a.s.l.]	373.2
Altitude of north portal [ft a.s.l.]	800.9	Altitude of north portal [ft a.s.l.]	812.2
Altitude of lowest point [ft a.s.l.]	256.4	Altitude of lowest point [ft a.s.l.]	276.4
Altitude of highest point [ft a.s.l.]	800.9	Altitude of highest point [ft a.s.l.]	812.2
Number of pedestrian escape doors [pcs]	39	Number of pedestrian escape doors [pcs]	37
Number of vehicle cross passages [pcs]	7	Number of vehicle cross passages [pcs]	7
South Portal		**South Portal**	
Geometric Data of Cut & Cover Section		**Geometric Data of Cut & Cover Section**	
Length [ft]	1885	Length [ft]	1130
Area of traffic area [ft²]	910.7	Area of traffic area [ft²]	910.7
Perimeter of traffic area [ft]	134.8	Perimeter of traffic area [ft]	134.8
Hydraulic diameter of traffic area [ft]	27.0	Hydraulic diameter of traffic area [ft]	27.0
Area of walkway [ft²]	74.8	Area of walkway [ft²]	74.8
Perimeter of walkway [ft]	45.4	Perimeter of walkway [ft]	45.4
Hydraulic diameter of walkway [ft]	6.6	Hydraulic diameter of walkway [ft]	6.6
North Portal		**North Portal**	
Geometric Data of Cut & Cover Section		**Geometric Data of Cut & Cover Section**	
Length [ft]	1640	Length [ft]	1388.7
Area of traffic area [ft²]	910.7	Area of traffic area [ft²]	910.7
Perimeter of traffic area [ft]	134.8	Perimeter of traffic area [ft]	134.8
Hydraulic diameter of traffic area [ft]	27.0	Hydraulic diameter of traffic area [ft]	27.0
Area of walkway [ft²]	74.8	Area of walkway [ft²]	74.8
Perimeter of walkway [ft]	45.4	Perimeter of walkway [ft]	45.4
Hydraulic diameter of walkway [ft]	6.6	Hydraulic diameter of walkway [ft]	6.6
Geometric Data of TBM Section		**Geometric Data of TBM Section**	
Length [ft]	22340	Length [ft]	22340
Area of traffic area [ft²]	623.3	Area of traffic area [ft²]	721.5
Perimeter of traffic area [ft]	103.5	Perimeter of traffic area [ft]	105.2
Hydraulic diameter of traffic area [ft]	24.1	Hydraulic diameter of traffic area [ft]	27.4
Area of walkway [ft²]	59.2	Area of walkway [ft²]	65.0
Perimeter of walkway [ft]	31.5	Perimeter of walkway [ft]	37.6
Hydraulic diameter of walkway [ft]	7.5	Hydraulic diameter of walkway [ft]	6.9

Area of exhaust duct [ft²]	169.2
Perimeter of exhaust duct [ft]	75.5
Hydraulic diameter of exhaust duct [ft]	9.0

Lanes per direction	2 + shoulder lane
Type of operation	unidirectional traffic

Table 2-2: Dual-Bore South Bound

Geometrical Data			
Lower Deck		**Upper Deck**	
Length [ft]	25745	Length [ft]	24853.7
South portal [ft]	1440+35.00	South portal [ft]	1446+75.00
North portal [ft]	1739+80.00	North portal [ft]	1737+28.70
Altitude of south portal [ft a.s.l.]	375.4	Altitude of south portal [ft a.s.l.]	373.0
Altitude of north portal [ft a.s.l.]	800.9	Altitude of north portal [ft a.s.l.]	812.2
Altitude of lowest point [ft a.s.l.]	256.4	Altitude of lowest point [ft a.s.l.]	276.4
Altitude of highest point [ft a.s.l.]	800.9	Altitude of highest point [ft a.s.l.]	812.2
Number of pedestrian escape doors [pcs]	39	Number of pedestrian escape doors [pcs]	37
Number of vehicle cross passages [pcs]	7	Number of vehicle cross passages [pcs]	7
South Portal		**South Portal**	
Geometric Data of Cut & Cover Section		**Geometric Data of Cut & Cover Section**	
Length [ft]	1765	Length [ft]	1125
Area of traffic area [ft²]	910.7	Area of traffic area [ft²]	910.7
Perimeter of traffic area [ft]	134.8	Perimeter of traffic area [ft]	134.8
Hydraulic diameter of traffic area [ft]	27.0	Hydraulic diameter of traffic area [ft]	27.0
Area of walkway [ft²]	74.8	Area of walkway [ft²]	74.8
Perimeter of walkway [ft]	45.4	Perimeter of walkway [ft]	45.4
Hydraulic diameter of walkway [ft]	6.6	Hydraulic diameter of walkway [ft]	6.6
North Portal		**North Portal**	
Geometric Data of Cut & Cover Section		**Geometric Data of Cut & Cover Section**	
Length [ft]	1640	Length [ft]	1388.7
Area of traffic area [ft²]	910.7	Area of traffic area [ft²]	910.7
Perimeter of traffic area [ft]	134.8	Perimeter of traffic area [ft]	134.8
Hydraulic diameter of traffic area [ft]	27.0	Hydraulic diameter of traffic area [ft]	27.0
Area of walkway [ft²]	74.8	Area of walkway [ft²]	74.8
Perimeter of walkway [ft]	45.4	Perimeter of walkway [ft]	45.4
Hydraulic diameter of walkway [ft]	6.6	Hydraulic diameter of walkway [ft]	6.6
Geometric Data of TBM Section		**Geometric Data of TBM Section**	
Length [ft]	22340	Length [ft]	22340
Area of traffic area [ft²]	623.3	Area of traffic area [ft²]	721.8
Perimeter of traffic area [ft]	103.5	Perimeter of traffic area [ft]	105.2
Hydraulic diameter of traffic area [ft]	24.1	Hydraulic diameter of traffic area [ft]	27.4
Area of walkway [ft²]	59.2	Area of walkway [ft²]	65.8
Perimeter of walkway [ft]	31.5	Perimeter of walkway [ft]	37.6
Hydraulic diameter of walkway [ft]	7.5	Hydraulic diameter of walkway [ft]	7.0

Area of exhaust duct [ft²]	169.2
Perimeter of exhaust duct [ft]	75.5
Hydraulic diameter of exhaust duct [ft]	9.0

Lanes per direction	2 + shoulder lane
Type of operation	unidirectional traffic

Table 2-3: Single-Bore

Geometrical Data			
Lower Deck		**Upper Deck**	
Length [ft]	22340	Length [ft]	22340
South portal [ft]	1440+35.00	South portal [ft]	1446+75.00
North portal [ft]	1739+80.00	North portal [ft]	1737+28.70
Altitude of south portal [ft a.s.l.]	313.6	Altitude of south portal [ft a.s.l.]	333.6
Altitude of north portal [ft a.s.l.]	744.3	Altitude of north portal [ft a.s.l.]	764.3
Altitude of lowest point [ft a.s.l.]	256.4	Altitude of lowest point [ft a.s.l.]	276.4
Altitude of highest point [ft a.s.l.]	744.3	Altitude of highest point [ft a.s.l.]	764.3
Number of pedestrian escape doors [pcs]	34	Number of pedestrian escape doors [pcs]	34
Number of vehicle cross passages [pcs]	7	Number of vehicle cross passages [pcs]	7
South Portal		**South Portal**	
Geometric Data of Cut & Cover Section		**Geometric Data of Cut & Cover Section**	
Length [ft]	0	Length [ft]	0
Area of traffic area [ft²]	910.7	Area of traffic area [ft²]	910.7
Perimeter of traffic area [ft]	134.8	Perimeter of traffic area [ft]	134.8
Hydraulic diameter of traffic area [ft]	27.0	Hydraulic diameter of traffic area [ft]	27.0
Area of walkway [ft²]	74.8	Area of walkway [ft²]	74.8
Perimeter of walkway [ft]	45.4	Perimeter of walkway [ft]	45.4
Hydraulic diameter of walkway [ft]	6.6	Hydraulic diameter of walkway [ft]	6.6
North Portal		**North Portal**	
Geometric Data of Cut & Cover Section		**Geometric Data of Cut & Cover Section**	
Length [ft]	0	Length [ft]	0
Area of traffic area [ft²]	910.7	Area of traffic area [ft²]	910.7
Perimeter of traffic area [ft]	134.8	Perimeter of traffic area [ft]	134.8
Hydraulic diameter of traffic area [ft]	27.0	Hydraulic diameter of traffic area [ft]	27.0
Area of walkway [ft²]	74.8	Area of walkway [ft²]	74.8
Perimeter of walkway [ft]	45.4	Perimeter of walkway [ft]	45.4
Hydraulic diameter of walkway [ft]	6.6	Hydraulic diameter of walkway [ft]	6.6
Geometric Data of TBM Section		**Geometric Data of TBM Section**	
Length [ft]	22340	Length [ft]	22340
Area of traffic area [ft²]	623.3	Area of traffic area [ft²]	721.8
Perimeter of traffic area [ft]	103.5	Perimeter of traffic area [ft]	105.2
Hydraulic diameter of traffic area [ft]	24.1	Hydraulic diameter of traffic area [ft]	27.4
Area of walkway [ft²]	59.2	Area of walkway [ft²]	65.8
Perimeter of walkway [ft]	31.5	Perimeter of walkway [ft]	37.6
Hydraulic diameter of walkway [ft]	7.5	Hydraulic diameter of walkway [ft]	7.0

Area of exhaust duct [ft²]	169.2
Perimeter of exhaust duct [ft]	75.5
Hydraulic diameter of exhaust duct [ft]	9.0

Lanes per direction	2 + shoulder lane
Type of operation	unidirectional traffic

2.2 Guidelines

This chapter points up the guidelines, which are fundamental for the dimensioning of a ventilation system for road tunnels.

2.2.1 NFPA 502 [1]

According to the NFPA 502 emergency ventilation shall be required in tunnels exceeding a length of 3,280 ft. Since the FWT exceed this length, a mechanical emergency ventilation system is necessary. All requirements and definitions of the NFPA, which are essential for the dimensioning of the emergency ventilation are summarized in this chapter.

2.2.1.1 Design Objectives for Unidirectional Traffic

- Longitudinal airflow rates are produced to prevent backlayering of smoke in a path of egress away from a fire.
- Create a longitudinal airflow in the direction of traffic flow by operating the upstream ventilation zone(s) in maximum supply and the downstream ventilation zone(s) in maximum exhaust.
- Avoid disruption of the smoke layer initially by not operating jet fans that are located near the fire site.
- Maximize the exhaust flow rate in the ventilation zone that contains the fire and minimize the amount of outside air that is introduced by a transverse system.

2.2.1.2 Requirements on Ventilation Equipment

- Tunnel ventilation fans, their motors, and all components critical to the operation of the system during fire emergency that can be exposed to elevated temperatures from the fire shall be designed to remain operational for a minimum of 1 hour at the temperature of 482°F.
- All dampers, actuators, and accessories that are exposed to the elevated exhaust airstream from the roadway fire shall be designed to remain fully operational in an airstream temperature of 482°F for at least 1 hour.
- The design of ventilation systems where fans can be directly exposed to a fire shall incorporate fan redundancy.
- The emergency ventilation system shall be capable of reaching full operational mode within a maximum of 180 seconds of activation.

2.2.1.3 Velocity Criteria

Air velocities in the enclosed tunnel should be greater than or equal to 150 fpm and less than or equal to 2,200 fpm. The minimum air velocity within a tunnel section that is experiencing a fire emergency should be sufficient to prevent backlayering of smoke.

The simultaneous solution of the following equations, by iteration, determines the critical velocity. The critical air velocity in the path of evacuation shall not be less than that required to control the direction of spread of smoke and hot gases. The calculation of the critical air velocity is detailed in the NFPA 502.

$$V_C = K_g \left(\frac{g * H * E_C}{Fr_C * \rho_\infty * C_p * A * T_f} \right)^{1/3}$$

$$T_f = \frac{E_C}{\rho_\infty * C_p * A * V_C} + T_\infty$$

where:	V_C	=	critical velocity	m/s (ft/s)
	g	=	acceleration of gravity	m/s^2 (ft/s^2)
	H	=	tunnel height	m (ft)
	E_C	=	the convective fire heat release rate	W (Btu/s)
	ρ_∞	=	ambient air density	kg/m^3 (lbm/ft^3)
	C_p	=	specific heat of air at constant pressure	J/kgK Btu/(lbm°R)
	A	=	net annular cross-sectional area of tunnel	m^2 (ft^2)
	T_f	=	hot gas temperature	K (°R)
	Fr_C	=	critical value of the Froude Number for a flow ventilating a fire	=4.5
	K_g	=	grade correction factor	Dimensionless
	T_∞	=	ambient temperature	K (°R)

2.2.1.4 Air Temperature Criteria

Motorists should not be exposed to maximum air temperatures that exceed 140°F during emergencies.

2.1 Traffic Data

2.1.1 Annual Average Daily Traffic (AADT)

The following traffic data are used for the fresh air calculations and the self-ventilation investigation. The traffic data have been provided by CH2M Hill [21] for the 1st year of operation (2025) and the 10th year of operation (2035). Table 2-4 gives the traffic volume in the form of **A**nnual **A**verage **D**aily **T**raffic (AADT) values for the single bore tunnel as well as for the dual bore tunnel. Weekdays and weekends are distinguished as well as peak periods AM and PM.

Table 2-4: Traffic Volume for Single Bore Tunnel and Dual Bore Tunnel, 2025 and 2035

Single Bore Tunnel 2025	AM Peak Period (6-9 AM) [veh]	PM Peak Period (3-7 PM) [veh]	Daily (AADT) [veh/d]
Weekday	14,900	19,400	**88,800**
Weekend	7,450	17,900	**81,200**
Single Bore Tunnel 2035			
Weekday	15,100	19,900	**89,900**
Weekend	7,550	18,350	**82,200**
Dual Bore Tunnel 2025			
Weekday	31,500	44,900	**180,200**
Weekend	15,750	41,350	**164,750**

Dual Bore Tunnel 2035			
Weekday	31,900	45,600	**182,200**
Weekend	15,950	42,000	**166,600**

Table 2-5 shows the percentage of heavy-goods vehicles (HGV) for the single bore tunnel and for the Dual bore tunnel.

Table 2-5: Percentage of HGV for Single Bore Tunnel and Dual Bore Tunnel, 2025 and 2035

Single Bore Tunnel 2025	AM Peak Period (6-9 AM) [%]	PM Peak Period (3-7 PM) [%]	Daily [%]
Weekday	8.2	10.5	**13.9**
Weekend	8.2	10.5	**13.9**
Single Bore Tunnel 2035			
Weekday	9.9	12.5	**16.7**
Weekend	9.9	12.5	**16.7**
Dual Bore Tunnel 2025			
Weekday	8.1	7.4	**12.3**
Weekend	8.1	7.4	**12.3**
Dual Bore Tunnel 2035			
Weekday	9.4	8.6	**14.0**
Weekend	9.4	8.6	**14.0**

For the single bore tunnel, the critical design criteria regarding the annual average daily traffic (AADT) is 89,900 veh/d for a weekday in 2035 incl. 16.7% HGV. For the Dual bore tunnel, the critical design criteria regarding the average daily traffic volume (AADT) is 182,200 veh/d for a weekday in 2035 incl. 14.0% HGV. The average daily traffic data in Table 2-4 apply to the whole tunnel (4 lanes in the single bore tunnel, 8 lanes in the Dual bore tunnel).

2.1.2 Hourly Traffic Volume (HT)

The AADT is converted into an hourly traffic (HT). The HT is 11% of the AADT in case of long-distance traffic and commuter traffic. The resulting HT in vehicles per hour is transformed to an HT in passenger car units (PCU) per hour by consideration of the heavy goods vehicle (HGV) equivalent [20]. Table 2-6 lists the hourly traffic per lane in PCU per hour for the single bore tunnel as well as for the Dual bore tunnel for the year 2025 and 2035.

Table 2-6: Hourly Traffic Volume for Single Bore Tunnel and Dual Bore Tunnel, 2025 and 2035

Single Bore Tunnel 2025	Hourly Traffic Volume (HT) per lane [PCU/h]
Weekday	**2,781**
Single Bore Tunnel 2035	
Weekday	**2,885**
Dual Bore Tunnel 2025	
Weekday	**2,783**
Dual Bore Tunnel 2035	
Weekday	**2,856**

The HT in PCU per hour is equally split on all lanes. Heavy-goods vehicles are assumed to drive on both lanes.

The HT per lane is limited to the maximum traffic volume M_{max}, which depends on the traffic speed (cp. Table 2-7). The maximum traffic volume M_{max} is based on safety and psychological aspects regarding the distance between vehicles in a tunnel. The minimum of the above calculated HT and M_{max} is considered within further ventilation design. It is called M_{dim}.

Table 2-7: Maximum traffic volume M_{max} per lane for one-directional traffic and different traffic speeds

traffic speed [mph]	0	6.2	12.4	24.9	37.3	49.7	62.1	74.6
M_{max} [PCU/h/lane]	0	1,100	1,850	2,280	2,400	2,225	2,000	1,750

M_{dim} is used to calculate the traffic density (D) using the following equation:

$$D = \frac{D_0 * M_{\dim}}{D_0 * v + M_{\dim}(1 - \frac{v}{v_0})^2} \qquad (1)$$

D	: traffic density	[PCU/mile]
D_0	: maximum traffic density	[PCU/mile]
$M_{\dim}$	: hourly traffic design volume	[PCU/h]
v	: traffic speed	[mph]
v_0	: optimum traffic speed	[mph]

The maximum traffic volume occurs at an optimum speed (v_0) of 40 mph. The maximum traffic density (D_0) is defined with 242 PCU/mile during traffic congestion.

The percentage of diesel vehicles is 7%. The main mass of trucks is defined with 88,000 lb. HGV equivalent with 2.0 PCU/HGV.

2.2 Meteorology

Wind pressure, buoyancy as well as barometric pressure differences between both tunnel portals affect the tunnel ventilation system and therefore have to be considered in the ventilation design. Within the following chapter, relevant pressure differences due to meteorological conditions are investigated. The analysis of meteorological pressure differences is based on measurement data of three metrological measurement stations. Figure 2-4 illustrates the locations of the tunnel portals and the locations of measurement stations, which are used for the determination of the pressure difference between the tunnel portals.

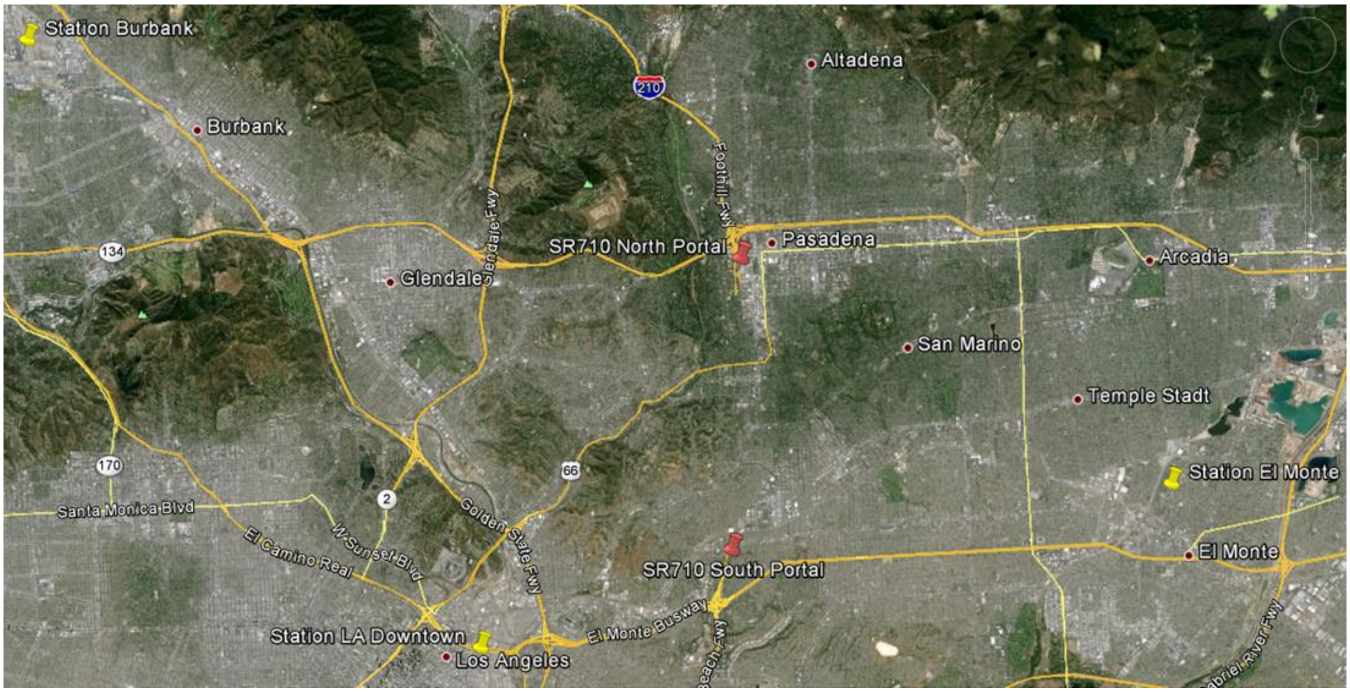


Figure 2-4: Location of Measurement Stations and Tunnel Portals (Source: Google Earth)

The datasets consist of hourly averaged values for wind speed, wind direction, temperatures and static pressure during the time period of the year 2011.

2.2.1 Static Pressure Difference

The datasets of the measurement stations have been used to determine a pressure trend over time at the location of the stations. The pressure trend over time at the tunnel portals were interpolated between the measurement stations. Table 2-8 shows the results of the pressure analysis.

Table 2-8: Static Pressure Loads on the Tunnel Portals

Percentile	South Portal [in.wg]	North Portal [in.wg]
95-Percentile	0.293	0.205

2.2.2 Pressure Difference Caused by Wind

Figure 2-5 illustrates the wind rose of the measurement station at LA Downtown. The wind rose shows a highly developed eastbound respectively westbound air flow. Wind velocities of 4 mph and higher are the most frequent as can be seen in Figure 2-6.

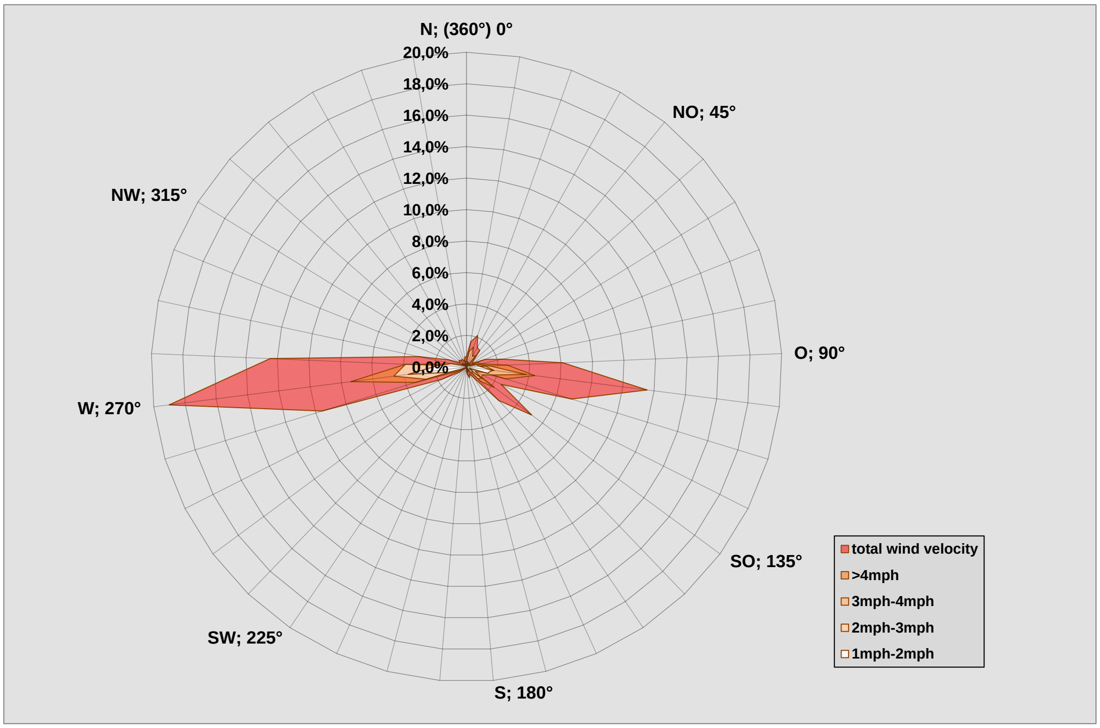


Figure 2-5: Wind Rose

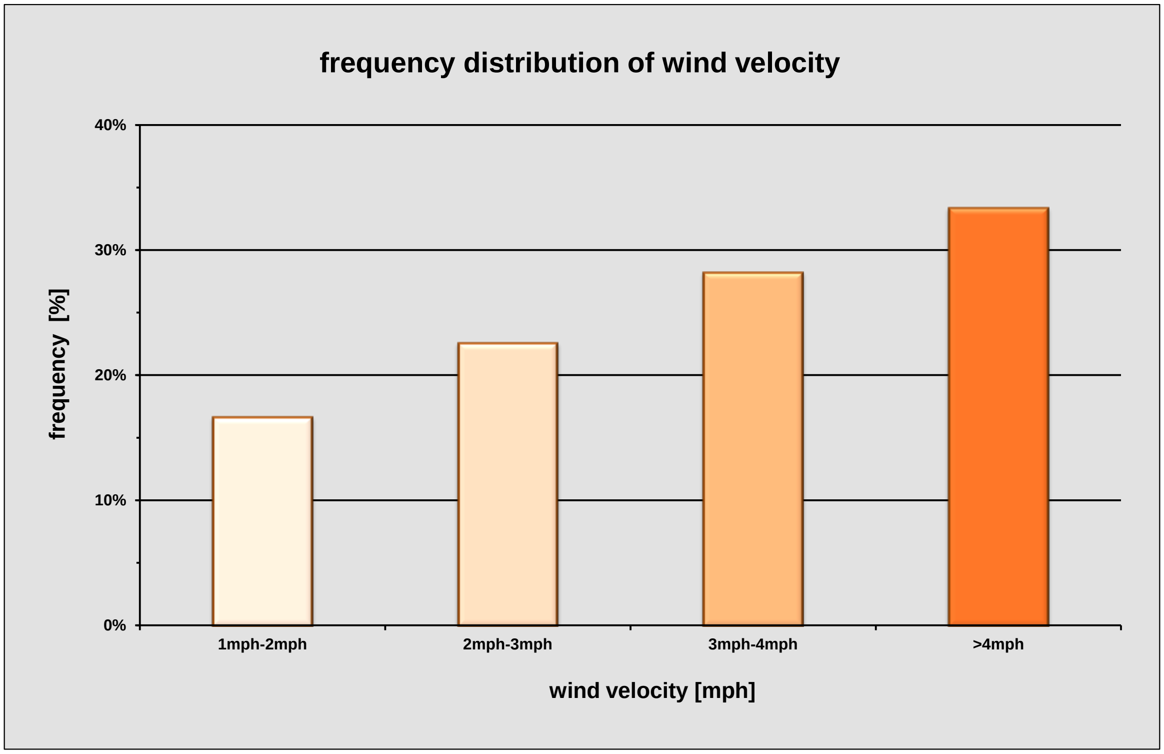


Figure 2-6: Frequency Distribution of Wind Speeds

To determine the pressure difference resulting from wind loads, the 95-percentile of all wind components normal to the portal has been calculated. Due to the portal orientation, the 95-percentile differs for the north and the south portal. Table 2-9 lists different percentiles of the wind speed components normal to the portal for the north portal as well as for the south portal. The 95 percentile of the wind speed component normal to the south portal is **437 fpm**. The 95 percentile of the wind speed component normal to the north portal is **315 ft/min**.

Table 2-9: Percentile of Wind Speed Components Normal to the Portal

Wind Speed acting on Portals				
Percentile	South Portal		North Portal	
95	437	fpm	315	fpm

The 95-percentile of the wind speed normal to the portal can be transformed into a pressure load. The results are shown in Table 2-10. The meteorological Pressure Load on the South Portal corresponding to the 95-percenile of the wind speeds is **0.012 in.wg**. The meteorological Pressure Load on the North Portal corresponding to the 95-percenile of the wind speeds is **0.006 in.wg**.

Table 2-10: Meteorological Pressure Load on the Tunnel Portals

Meteorolical Pressure Load on Tunnel Portals				
Percentile	South Portal		North Portal	
95	0,012	in.wg	0,006	in.wg

2.2.3 Pressure Difference Due To Natural Buoyancy

The tunnel wall temperature and the air temperature outside the tunnel usually not the same. In summer the outside air temperature will be higher and in winter the outside air temperature will be lower than the tunnel wall temperature. The temperature difference is equal to a density difference, which causes buoyancy effects. The buoyancy in turn causes a pressure difference which affects the ventilation system. Figure 2-7 illustrates the temperature curve of the measurement station LA Downtown for the year 2011.

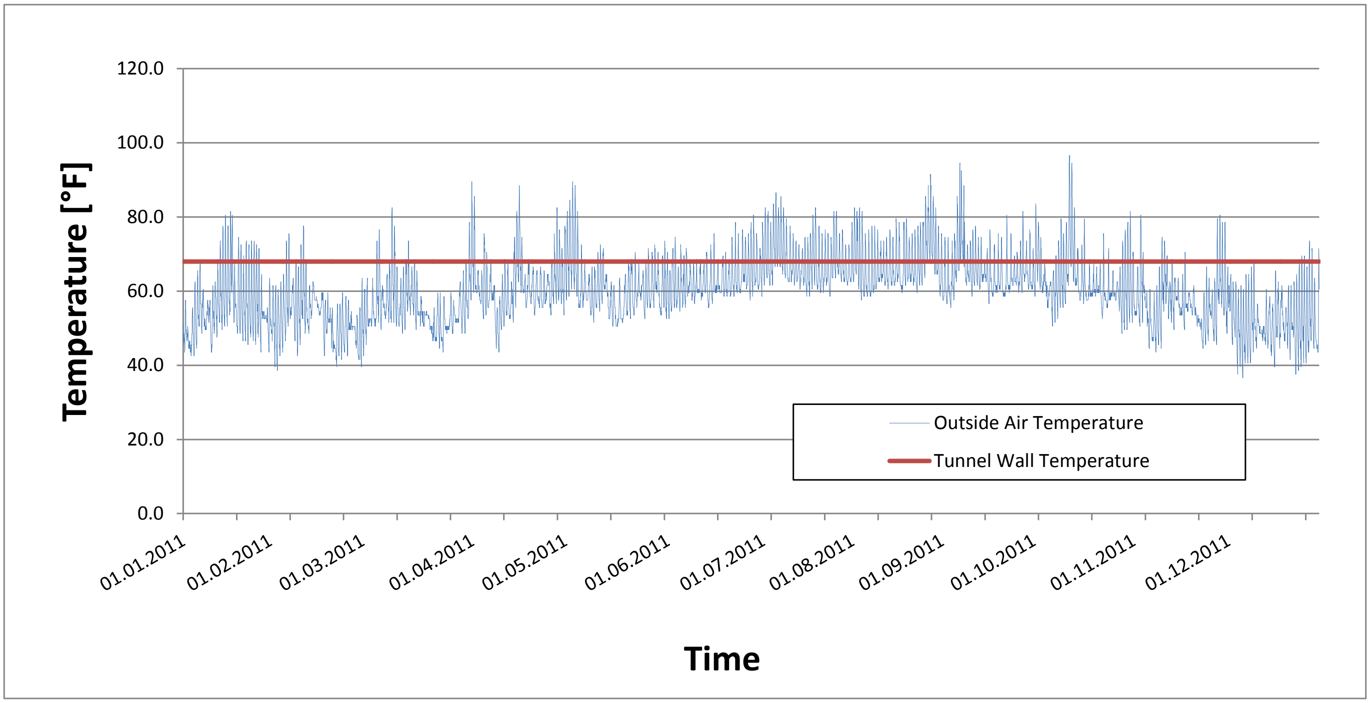


Figure 2-7: Temperature Curve for at the Measurement Station LA Downtown

A conservative assumption for the tunnel wall temperature is 68°F. The air inside the tunnel will attain the tunnel wall temperature. The temperature difference between tunnel air and outside air and the height difference between South Portal and North Portal cause a pressure difference. The calculated pressure differences can be read from Table 2-11.

Table 2-11: Pressure Difference Caused by Buoyancy

Pressure load Natural Buoyancy		
Percentile	South Portal	North Portal
95	0.266 in.wg	0.089 in.wg

2.2.4 Entire Portal Pressure Difference

The entire pressure difference is the sum of all individual pressure differences. Table 2-12 shows the results of the entire portal pressure difference. An approximately 10-15% safety margin has been added to the entire pressure difference to take into account the potential inaccuracy due to the distances of the measurements stations to the tunnel portals.

Table 2-12: Entire Portal Pressure Difference

Pressure Difference	South Portal [in.wg]	North Portal [in.wg]
Static Pressure Difference	0.293	0.205
Cuased by Wind	0.012	0.006
Cuased by Buoancy	0.266	0.089
Entire Pressure Difference	0.571	0.299
Entire Pressure Difference + Safety Margin	**0.660**	**0.330**

2.3 Used Simulation Software

2.3.1 NUMSTA3

The tunnel system is simulated using the software program NUMSTA3 (NUMerical Simulation of Tunnel Aerodynamics). The basic of NUMSTA is a one-dimensional, conservative form of the transient, incompressible Euler Equations. Mass transfer, friction and heat transfer are considered in additional source terms following the idea of the “distributed loss model”. A numeric scheme of second order accuracy, based on the Roe Scheme, is used to discretize the system with a finite volume approach. NUMSTA3 generates a three-dimensional tube model of the tunnel system, which is split up into segments depending on the defined resolution. NUMSTA3 uses a higher numerical standard than SES Version 4.1. NUMSTA3 considers a compressible formulation instead of an incompressible flow used by SES Version 4.1 (NUMSTA3 computes more complex physical equations than SES). SES was developed in 1976. The computer power of that era did not allow consideration of compressible calculations. The method of characteristics calculation was never upgraded even though computer power increased.

2.3.2 OpenFOAM

OpenFOAM is foremost a C++ library, used primarily to create executables, known as applications. The applications fall into two categories: solvers that are each designed to solve a specific problem in continuum mechanics, and utilities that are designed to perform tasks that involve data manipulation. OpenFOAM has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence and heat transfer, to solid dynamics and electromagnetism.

Ventilation System for Normal Operation

3.1 Ventilation Concept for Normal Operation

For both, the single and the dual bore alternative, the same ventilation concept is applied. Figure 3-1 shows the ventilation concept for the example of the dual bore alternative. The piston effect of the driving cars produces an air velocity in the tunnel. In a tube with southbound lanes, the tunnel air flows from the north portal to the south portal. Therefore, the tunnel air is pulled into the exhaust duct of the Ventilation Building South. In a tube with northbound lanes, the tunnel air is pulled into the exhaust duct of the Ventilation Building North. Jet fans near the portals support the piston effect of the driving cars and help to produce the necessary flow rate in the tunnel. The tunnel air flows through the air scrubbing unit, where particles are separated from the air. The scrubbed air passes though the exhaust fan and flows into the outdoor ambient air.

The exhaust duct for normal operation and the air scrubbing unit are represented by the blue parts in Figure 3-1. The shutting dampers between the exhaust ducts for emergency operation are closed.

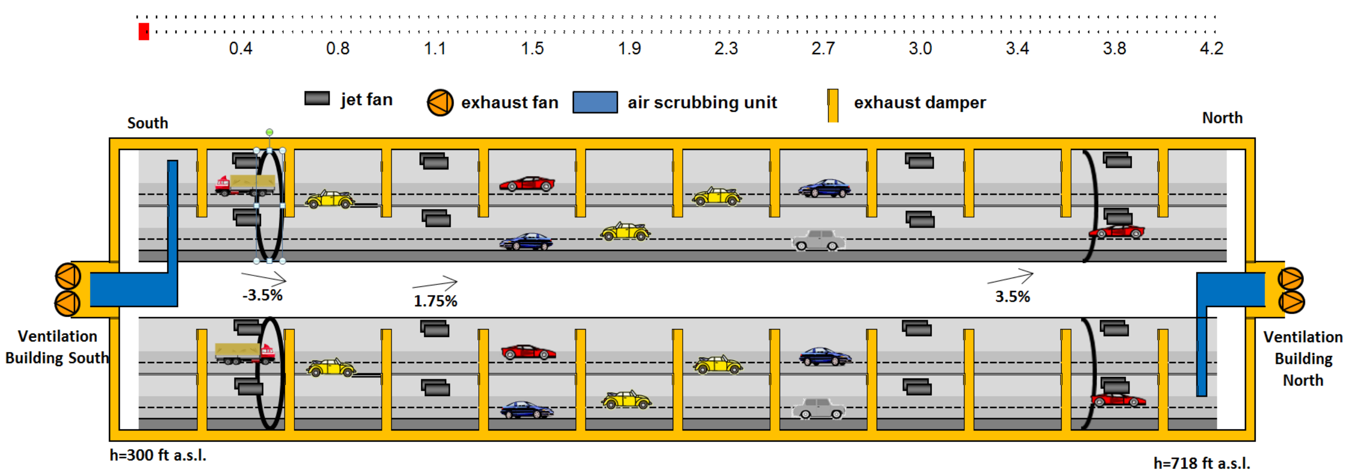


Figure 3-1: Ventilation Concept Scheme, Dual Bore Alternative

3.2 Fresh Air Requirements

Detailed emission data of California are the basis for many environmental studies. The use of the different models, i.e. MOBILE6, MOVES2010 and EMFAC has been discussed and it was found that the emission factors as in the EMission FActors for California (EMFAC) model is applicable for this particular project.

As this data is very detailed in terms of the vehicle categories and the pollutant types, a method had to be established how these values can be used to calculate the fresh air requirement in a tunnel ventilation project. The Technical Memorandum “Using EMFAC2011 Emission Values as a Basis to Calculate the Fresh Air Requirement” [20] summarizes the input for the fresh air calculation.

3.2.1.1 EMFAC Web Based Data Access

Due to the increased complexity of EMFAC2011 compared to its predecessor EMFAC2007, data can be accessed via a web interface. EMFAC contains the emission values from 51 vehicle categories, where Diesel and gasoline driven vehicles from the same type account for 2 categories, in speed steps of 5 mph. The emission values for various pollutant gases and for particulate matter are given as both hourly rates in tons/hour and emissions per mile in grams/mile.

The EMFAC data base contains also information about the vehicle miles traveled (VMT) per day for each vehicle category and speed step. The data is made available on a regional basis which also respects the air basin boundaries [14]. For the tunnel, the data set of the South Coast air basin of Los Angeles is relevant, i.e. “Los Angeles (SC)” in the EMFAC2011 Web Access.

3.2.1.2 Converting EMFAC values to base emissions

The following steps have to be taken in order to convert the EMFAC emission values to base emissions required to calculate the fresh air requirement.

- Extraction of the emission values for CO, NOx and PM10[1] in g/h from EMFAC2011 for each vehicle category and speed step in the project area.
- Aggregation of the emission values for CO, NOx and PM10 in g/h for the following main vehicle categories:
  - passenger cars gas
  - passenger cars diesel
  - trucks

  The weighted balance of the emission values for all different vehicle categories contained in a higher level vehicle category is calculated using the EMFAC information about the vehicle miles traveled (VMT) per day in the South Coast air basin of Los Angeles.
- Steps 1 and 2 yield the base emission values for the 3 main vehicle categories and all speed steps at grade. The base emission values for the vehicles on a slope are calculated using the grade factors as they are given in the PIARC values for the USA [6]. These values are then converted into emissions in m^3/h for all speed steps using the densities CO=1.2 kg/m^3, NOx=1.9 kg/m^3 and for PM the conversion: 1 g = 4.7 m^2 [6].

Table 3-1: Base emission table for 0% slope using EMFAC [20]

EMFAC, car gasoline															
Speed	[mph]	0	3.125	6.25	12.5	18.75	25	31.25	37.5	43.75	50	56.25	62.5	68.75	75
CO	[m³/h]	0.00100	0.00385	0.00670	0.01189	0.01581	0.01896	0.02146	0.02364	0.02573	0.02788	0.03043	0.03463	0.04268	0.05275
NOX	[m³/h]	0.00008	0.00023	0.00038	0.00066	0.00086	0.00102	0.00119	0.00136	0.00152	0.00169	0.00198	0.00232	0.00269	0.00309
PM	[m³/h]	0.26212	0.31906	0.37600	0.44469	0.42297	0.38454	0.35555	0.34215	0.34715	0.37377	0.43336	0.54023	0.66688	0.78281
EMFAC, car Diesel															
Speed	[mph]	0	3.125	6.25	12.5	18.75	25	31.25	37.5	43.75	50	56.25	62.5	68.75	75
CO	[m³/h]	0.00856	0.01564	0.02271	0.02992	0.02293	0.01801	0.01894	0.02139	0.02111	0.02205	0.02847	0.03510	0.04351	0.05539
NOX	[m³/h]	0.00716	0.02111	0.03506	0.05463	0.05270	0.04947	0.05945	0.07527	0.07263	0.06571	0.08838	0.08376	0.05681	0.07103
PM	[m³/h]	1.63041	5.00267	8.37493	12.76121	11.42514	9.67152	10.59502	12.31207	11.84284	12.31795	16.47884	21.80609	30.32304	41.04297
EMFAC, trucks															
Speed	[mph]	0	3.125	6.25	12.5	18.75	25	31.25	37.5	43.75	50	56.25	62.5	68.75	75
CO	[m³/h]	0.00424	0.00791	0.01157	0.01745	0.02013	0.02342	0.02578	0.02736	0.02926	0.03195	0.03525	0.04114	0.04971	0.05923
NOX	[m³/h]	0.00175	0.00267	0.00359	0.00510	0.00623	0.00655	0.00875	0.01163	0.01414	0.01719	0.02275	0.03083	0.04033	0.04933
PM	[m³/h]	0.25411	0.43451	0.61491	0.92448	1.20546	1.26872	1.78779	2.68339	3.80676	5.51464	8.57660	13.24661	18.46294	23.18368

[1] PM10 values are particles with less than 10 µm in diameter; PM2.5 values are included the PM10 values

3.2.2 Application of the EMFAC base emission table on the fresh air calculation for a road tunnel

As the EMFAC database contains no information about vehicle emissions in a tunnel with a grade, the base emission values at grade have to be converted to the full base emission table considering the slope. The necessary slope coefficients are extracted from the base emission table according to PIARC [6] and used in the EMFAC base emission table. This implies that the relationship of emissions under a slope and at grade (not the absolute values) is the same in California as given by PIARC for the USA.

3.2.3 Air Quality Limits for CO, NO_2 and Visibility

Table 3-2: Threshold Values, [20]

Entity	Value
CO	35 ppm
Visibility	5 / km
NO2	1 ppm

3.2.4 Fresh Air Calculation

The fresh air requirement for the tunnel has been calculated using the method established above; the parameters as specified in Table 3-2 have been used. The following figures show the maximum necessary fresh air flow rate over vehicle speed for the single and dual bore alternative.

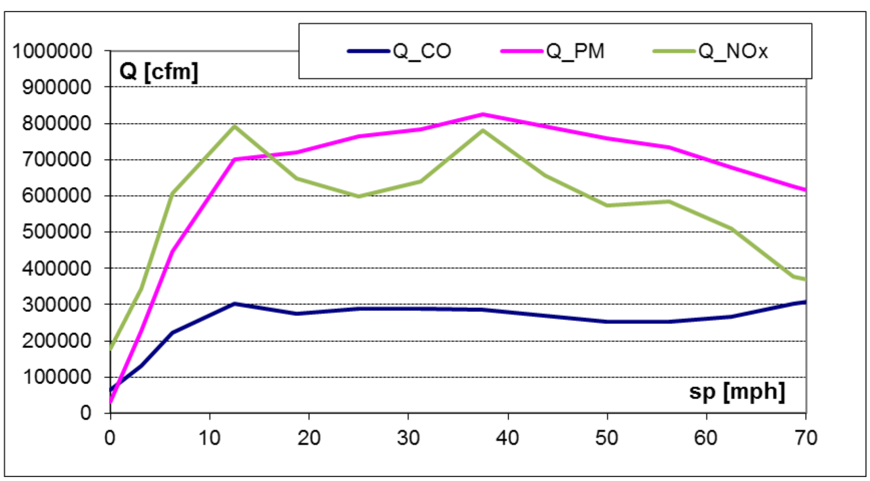


Figure 3-2: Fresh Air Requirement per Driving Deck, Uphill

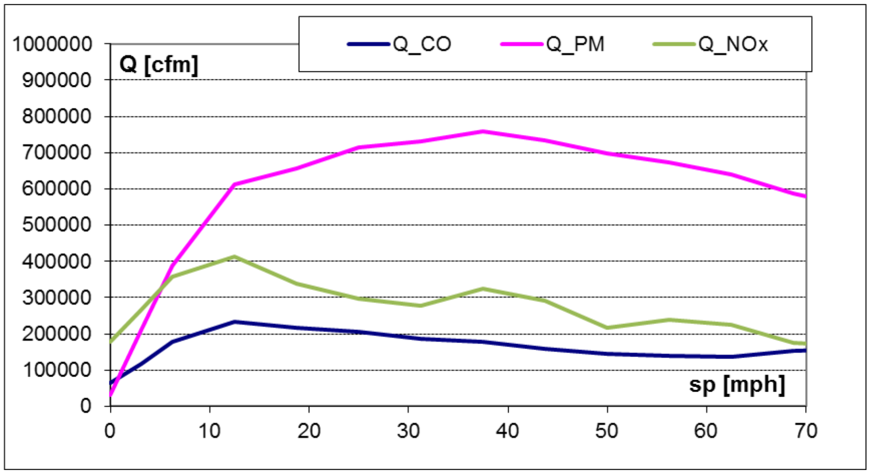


Figure 3-3: Fresh Air Requirement per Driving Deck, Downhill

For low velocities the NOx-emissions are decisive for the fresh air requirement of about 793,000 cfm. At higher velocities the PM-emissions are decisive for the fresh air requirement of about 826,000 cfm.

3.3 Investigation of Self-Ventilation

Operating vehicles are producing a piston effect. If this piston effect is higher than the meteorological pressure difference, vehicles produce an air velocity in the tunnel. From a certain vehicle speed on, the air velocity is sufficient to achieve the required fresh air flow rate for self-ventilation.

The calculations include a constant heat transfer model between tunnel wall and tunnel air. *Table 3-3* to *Table 3-6* shows a comparison of the required fresh air flow rates with the induced flow rates by the vehicles for both tubes at different meteorological pressure differences.

The red, blue and green curves show the induced flow rates by the vehicles at different meteorological pressure differences. The magenta curve shows the required fresh air defined in chapter.

Table 3-3: Self-Ventilation, Uphill, Upper Deck

self ventilation													
traffic velocity	**[mph]**	**0**	**3**	**6**	**12**	**19**	**25**	**31**	**37**	**43**	**50**	**56**	**62**
+0.66 in.wg	[fpm]	353.4	547.3	688.8	803.4	918.6	1063.8	1208.1	1345.7	1475.4	1597.3	1655.7	1712.5
+/- 0 in.wg	[fpm]	48.9	150.6	272.8	501.1	704.2	886.8	1052.8	1204.9	1345.0	1474.8	1536.4	1595.8
-0.33 in.wg	[fpm]	-254.5	-94.8	83.2	369.7	600.3	798.5	974.4	1133.4	1278.7	1412.5	1475.7	1536.4
fresh air requirement	[fpm]	245.2	478.0	841.8	1098.8	998.5	1059.5	1088.5	1145.3	1096.8	1054.1	1019.7	942.3

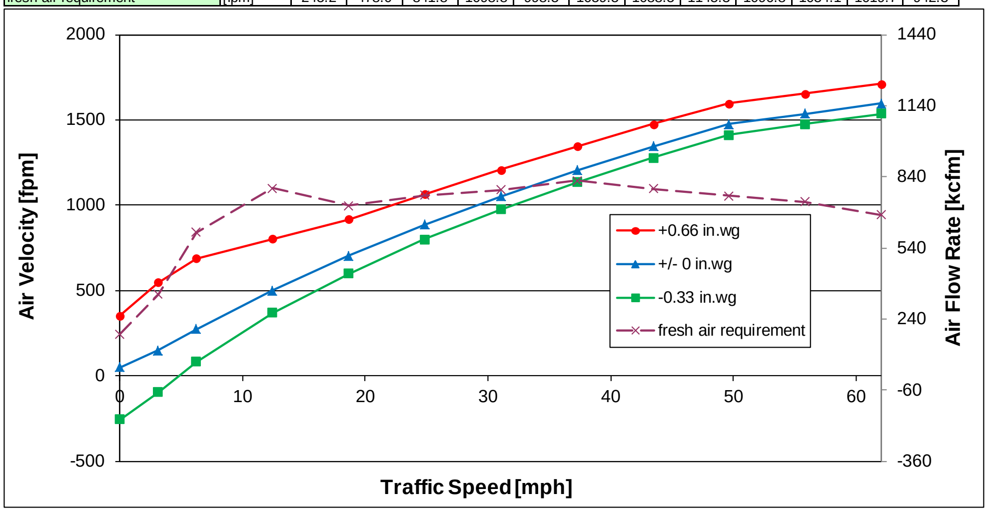


Table 3-4: Self-Ventilation, Uphill, Lower Deck

self ventilation													
traffic velocity	**[mph]**	**0**	**3**	**6**	**12**	**19**	**25**	**31**	**37**	**43**	**50**	**56**	**62**
+0.66 in.wg	[fpm]	289.4	456.6	577.5	677.6	788.3	920.0	1049.3	1172.2	1287.8	1396.2	1448.2	1498.8
+/- 0 in.wg	[fpm]	40.8	132.2	240.1	441.2	620.2	781.2	927.7	1061.9	1185.7	1300.4	1354.9	1407.5
-0.33 in.wg	[fpm]	-210.2	-68.4	86.6	335.6	536.9	710.5	864.9	1004.7	1132.6	1250.5	1306.3	1359.9
fresh air requirement	[fpm]	283.7	553.1	974.1	1271.5	1155.5	1226.0	1259.6	1325.3	1269.1	1219.7	1180.0	1090.4

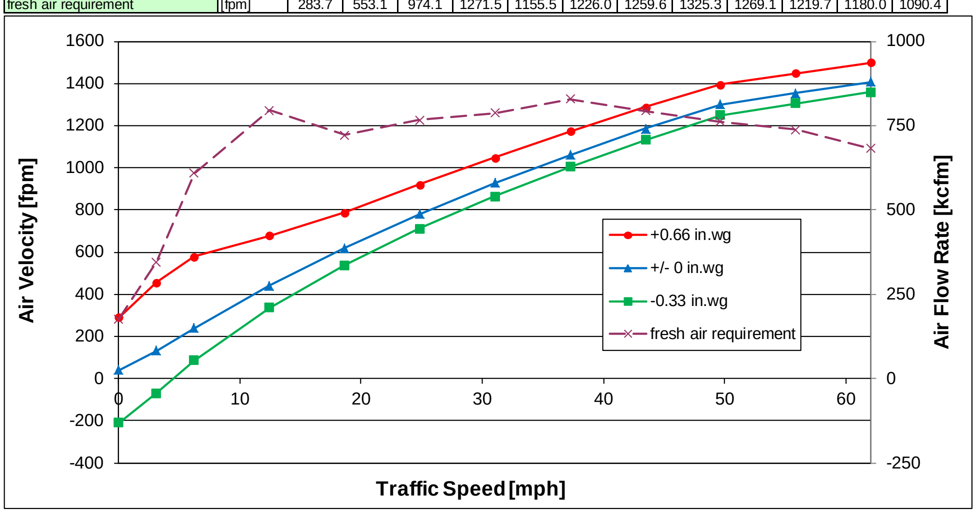


Table 3-5: Self-Ventilation, Downhill, Upper Deck

self ventilation													
traffic velocity	[mph]	0	3	6	12	19	25	31	37	43	50	56	62
+0.66 in.wg	[fpm]	-356.8	-221.1	-73.4	246.1	503.3	718.9	907.2	1075.4	1228.0	1367.7	1433.4	1496.3
+/- 0 in.wg	[fpm]	-65.1	124.5	266.3	504.2	711.7	897.5	1066.1	1220.5	1362.7	1494.3	1556.8	1617.1
-0.33 in.wg	[fpm]	248.3	428.5	539.8	649.3	819.0	986.9	1144.8	1291.9	1428.9	1556.6	1617.4	1676.4
fresh air requirement	[fpm]	245.2	372.5	540.2	852.5	913.1	992.5	1016.0	1055.5	1019.9	969.1	929.2	884.6

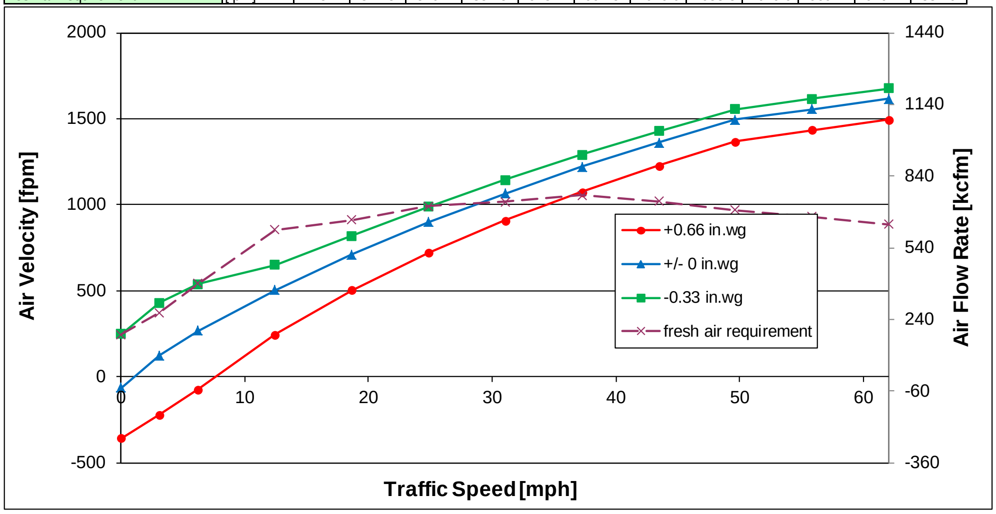
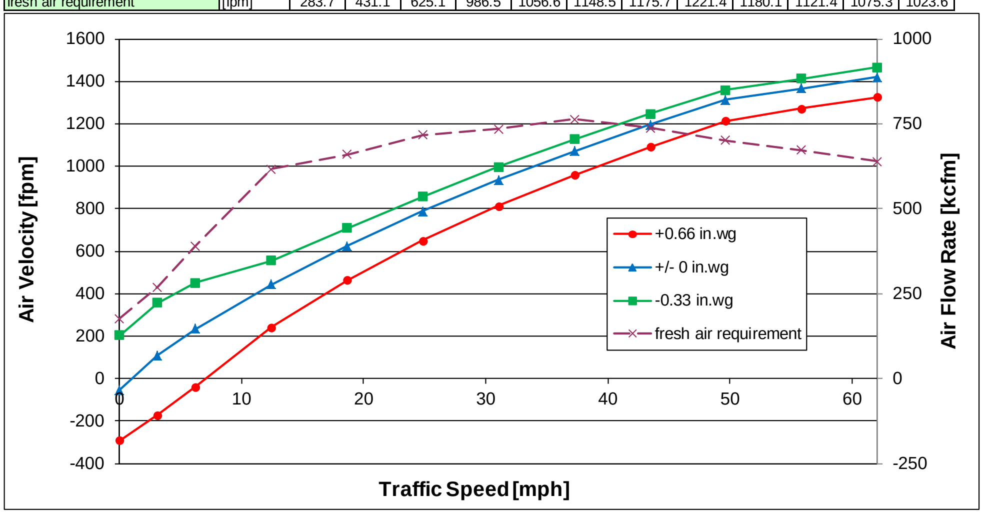


Table 3-6: Self-Ventilation, Downhill, Lower Deck

self ventilation													
traffic velocity	[mph]	0	3	6	12	19	25	31	37	43	50	56	62
+0.66 in.wg	[fpm]	-291.7	-170.7	-37.7	241.1	462.6	649.2	812.7	959.1	1092.1	1214.1	1271.6	1326.7
+/- 0 in.wg	[fpm]	-53.9	110.1	233.9	442.6	624.7	787.8	935.9	1071.5	1196.5	1312.2	1367.2	1420.2
-0.33 in.wg	[fpm]	202.4	357.3	450.8	555.2	708.1	857.3	997.1	1127.0	1247.9	1360.5	1414.2	1466.2
fresh air requirement	[fpm]	283.7	431.1	625.1	986.5	1056.6	1148.5	1175.7	1221.4	1180.1	1121.4	1075.3	1023.6



The investigation of self-ventilation shows that the piston effect from operating vehicles is sufficient at speeds above 25 mph to 50 mph. In situations with stop-and-go traffic the minimum speed for self-ventilation depends on the meteorological pressure difference.

A mechanical ventilation system is only needed in situations with stop-and-go traffic.

3.4 Pressure Loss in Ventilation Buildings

The air flow rates are used in the following pressure loss calculations. The path of the flowing air can be seen in the Figures of Section 3.6 and 4.4.

3.4.1 Ventilation Building South, Single Bore

Table 3-7: Pressure Loss in Exhaust Ducts of Ventilation Building South, Normal Operation

Number	Discription	Values									Remarks and Bibliography
		Cross Section	Perimeter	Hydraulic Diameter	Length	Flow Rate	Velocity	Friction Coefficient	Pressure Loss Coefficient	Pressure Loss	
		[ft²]	[ft]	[ft]	[ft]	[cfm]	[fpm]	[-]	[-]	[in.wg]	
1	Entrance into the System	96.9	39.4	9.8	-	69300	720	-	1.65	0.053	Experience Value
2	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	1.01	0.001	*D S Miller 13.32*
3	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.51	0.001	*D S Miller 13.32*
4	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.21	0.001	*D S Miller 13.32*
5	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.001	*D S Miller 13.32*
6	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.001	*D S Miller 13.32*
7	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.001	*D S Miller 13.32*
8	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.002	*D S Miller 13.32*
9	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.002	*D S Miller 13.32*
10	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.003	*D S Miller 13.32*
11	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.003	*D S Miller 13.32*
12	Filter	96.9	54.8	7.1	-	69300	720	-	0.00	0.642	According To Manufacturer
14	Shutting Damper	1067.5	61.4	69.6	-	762800	710	-	0.70	0.022	Experience Value
16	30° Rejuvenation	2228.7	106.3	22.4	-	762800	1280	-	0.04	0.004	*Idel'cik 5.23*
17	Entirely Ventilation Unit	-	-	-	-	762800	-	-	-	0.934	Efficiency 0.7
18	Air Duct	596.0	74.5	32.0	19.7	762800	1280	0.015	0.00	0.000	Wall Friction
19	Silencer	596.0	77.8	30.7	-	762800	1280	-	-	0.642	Experience Value
20	Air Duct	596.0	81.0	29.4	26.2	762800	1280	0.015	0.01	0.001	Wall Friction
21	90° Bend	596.0	84.3	28.3	-	762800	1280	-	1.70	0.173	*Idel'cik 6.6*
22	Air Duct	413.5	87.6	18.9	118.1	762800	1840	0.015	0.06	0.012	Wall Friction
23	Exit of the System	413.5	90.9	18.2	-	762800	1840	-	1.00	0.211	Entire Kinetic Energy is Lossed
24	Underpressure to traffic space	-	-	-	-	-	-	-	-	0.401	
25	**Sum**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**3.114**	

Table 3-8: Pressure Loss in Exhaust Ducts of Ventilation Building North, Normal Operation

Number	Discription	Values									Remarks and Bibliography
		Cross Section	Perimeter	Hydraulic Diameter	Length	Flow Rate	Velocity	Friction Coefficient	Pressure Loss Coefficient	Pressure Loss	
		[ft²]	[ft]	[ft]	[ft]	[cfm]	[fpm]	[-]	[-]	[in.wg]	
1	Entrance into the System	96.9	39.4	9.8	-	75100	780	-	1.65	0.062	Experience Value
2	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	1.01	0.001	*D S Miller 13.32*
3	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.51	0.001	*D S Miller 13.32*
4	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.21	0.001	*D S Miller 13.32*
5	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
6	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
7	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
8	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
9	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
10	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
11	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
12	Filter	96.9	39.4	9.8	-	75100	780	-	24.80	0.642	According To Manufacturer
13	Shutting Damper	1257.7	171.9	29.3	-	826300	660	-	0.70	0.019	Experience Value
15	30° Rejuvenation	669.8	115.5	23.2	-	1652700	2470	-	0.04	0.017	*Idel'cik 5.23*
16	Entirely Ventilation Unit	-	-	-	-	-	-	-	-	1.063	Efficiency 0.7
17	Air Duct	669.8	115.5	23.2	23.0	826300	1230	0.015	0.01	0.001	Wall Friction
18	Silencer	669.8	115.5	23.2	-	826300	1230	-	1.55	0.642	Experience Value
19	Air Duct	669.8	115.5	23.2	32.8	826300	1230	0.015	0.02	0.002	Wall Friction
20	90° Bend	669.8	115.5	23.2	-	826300	1230	-	1.70	0.161	Idel'cik 6.6
21	Air Duct	1148.3	138.4	33.2	16.4	826300	720	0.015	0.01	0.000	Wall Friction
22	90° Bend	451.1	105.0	17.2	-	826300	1830	-	0.81	0.169	Idel'cik 6.6
23	Air Duct	574.1	110.9	20.7	426.5	826300	1440	0.015	0.31	0.040	Wall Friction + 300ft Security
24	90° Bend	574.1	110.9	20.7	-	826300	1440	0.015	0.81	0.104	*Idel'cik 6.6*
25	Air Duct	464.8	105.6	17.6	118.1	826300	1780	0.015	0.10	0.020	Wall Friction
27	Exiting Loss	464.8	105.6	17.6	-	826300	1780	-	1.00	0.196	Entire Kinetic Energy is Lossed
28	Under Pressure to Traffic Space	-	-	-	-	-	-	-	-	0.401	-
29	**Sum**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**3.542**	

3.4.2 Ventilation Building South, Dual Bore

Table 3-9: Pressure Loss in Exhaust Ducts of Ventilation Building South, Normal Operation

Number	Discription	Values									Remarks and Bibliography
		Cross Section	Perimeter	Hydraulic Diameter	Length	Flow Rate	Velocity	Friction Coefficient	Pressure Loss Coefficient	Pressure Loss	
		[ft²]	[ft]	[ft]	[ft]	[cfm]	[fpm]	[-]	[-]	[in.wg]	
1	Entrance into the System	96.9	39.4	9.8	-	69300	720	-	1.65	0.053	Experience Value
2	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	1.01	0.001	*D S Miller 13.32*
3	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.51	0.001	*D S Miller 13.32*
4	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.21	0.001	*D S Miller 13.32*
5	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.001	*D S Miller 13.32*
6	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.001	*D S Miller 13.32*
7	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.001	*D S Miller 13.32*
8	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.002	*D S Miller 13.32*
9	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.002	*D S Miller 13.32*
10	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.003	*D S Miller 13.32*
11	Mixing of Two Flows	96.9	39.4	9.8	11.5	69300	720	0.015	0.11	0.003	*D S Miller 13.32*
12	Filter	96.9	54.8	7.1	-	69300	720	-	0.00	0.642	According To Manufacturer
14	Shutting Damper	1067.5	61.4	69.6	-	762800	710	-	0.70	0.022	Experience Value
16	30° Rejuvenation	2228.7	106.3	22.4	-	1525500	2560	-	0.04	0.018	*Idel'cik 5.23*
17	Entirely Ventilation Unit	-	-	-	-	1525500	-	-	-	1.442	Efficiency 0.7
18	Air Duct	596.0	74.5	32.0	19.7	1525500	2560	0.015	0.00	0.001	Wall Friction
19	Silencer	596.0	77.8	30.7	-	1525500	2560	-	-	0.642	Experience Value
20	Air Duct	596.0	81.0	29.4	26.2	1525500	2560	0.015	0.01	0.005	Wall Friction
21	90° Bend	596.0	84.3	28.3	-	1525500	2560	-	1.70	0.692	*Idel'cik 6.6*
22	Air Duct	413.5	87.6	18.9	118.1	1525500	3690	0.015	0.03	0.024	Wall Friction
23	Exit of the System	413.5	90.9	18.2	-	1525500	3690	-	1.00	0.846	Entire Kinetic Energy is Lossed
24	Underpressure to traffic space	-	-	-	-	-	-	-	-	0.401	
25	**Sum**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**4.806**	

Table 3-10: Pressure Loss in Exhaust Ducts of Ventilation Building North, Normal Operation

Number	Discription	Values									Remarks and Bibliography
		Cross Section	Perimeter	Hydraulic Diameter	Length	Flow Rate	Velocity	Friction Coefficient	Pressure Loss Coefficient	Pressure Loss	
		[ft²]	[ft]	[ft]	[ft]	[cfm]	[fpm]	[-]	[-]	[in.wg]	
1	Entrance into the System	96.9	39.4	9.8	-	75100	780	-	1.65	0.062	Experience Value
2	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	1.01	0.001	*D S Miller 13.32*
3	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.51	0.001	*D S Miller 13.32*
4	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.21	0.001	*D S Miller 13.32*
5	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
6	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
7	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
8	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
9	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
10	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
11	Mixing of Two Flows	96.9	39.4	9.8	11.5	75100	780	0.015	0.01	0.000	*D S Miller 13.32*
12	Filter	96.9	39.4	9.8	-	75100	780	-	24.80	0.642	According To Manufacturer
13	Shutting Damper	1257.7	171.9	29.3	-	826300	660	-	0.70	0.019	Experience Value
15	30° Rejuvenation	669.8	115.5	23.2	-	1652700	2470	-	0.04	0.017	*Idel'cik 5.23*
16	Entirely Ventilation Unit	-	-	-	-	-	-	-	-	1.955	Efficiency 0.7
17	Air Duct	669.8	115.5	23.2	23.0	1652700	2470	0.015	0.01	0.006	Wall Friction
18	Silencer	669.8	115.5	23.2	-	1652700	2470	-	1.55	0.642	Experience Value
19	Air Duct	669.8	115.5	23.2	32.8	1652700	2470	0.015	0.02	0.008	Wall Friction
20	90° Bend	669.8	115.5	23.2	-	1652700	2470	-	1.70	0.643	Idel'cik 6.6
21	Air Duct	1148.3	138.4	33.2	16.4	1652700	1440	0.015	0.01	0.001	Wall Friction
22	90° Bend	451.1	105.0	17.2	-	1652700	3660	-	0.81	0.676	Idel'cik 6.6
23	Air Duct	574.1	110.9	20.7	426.5	1652700	2880	0.015	0.31	0.159	Wall Friction + 300ft Security
24	90° Bend	574.1	110.9	20.7	-	1652700	2880	0.015	0.81	0.417	*Idel'cik 6.6*
25	Air Duct	464.8	105.6	17.6	118.1	1652700	3560	0.015	0.10	0.079	Wall Friction
27	Exiting Loss	464.8	105.6	17.6	-	1652700	3560	-	1.00	0.786	Entire Kinetic Energy is Lossed
28	Under Pressure to Traffic Space	-	-	-	-	-	-	-	-	0.401	-
29	**Sum**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**6.516**	

3.5 NUMSTA3 Simulations

The simulations in this chapter are performed to determine the necessary jet fan performance and the necessary amount of jet fans. The used NUMSTA3 simulation model is illustrated in Figure 3-4 and Figure 3-5.

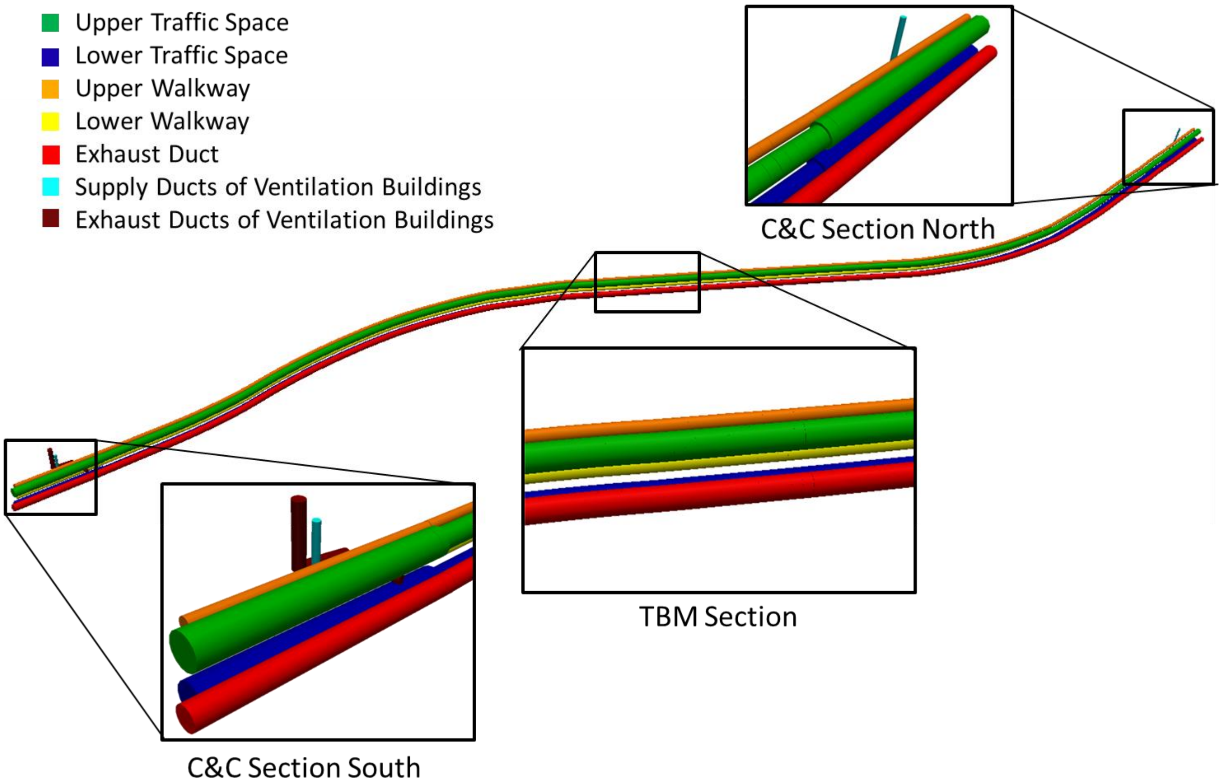


Figure 3-4: NUMSTA3 Simulation Model

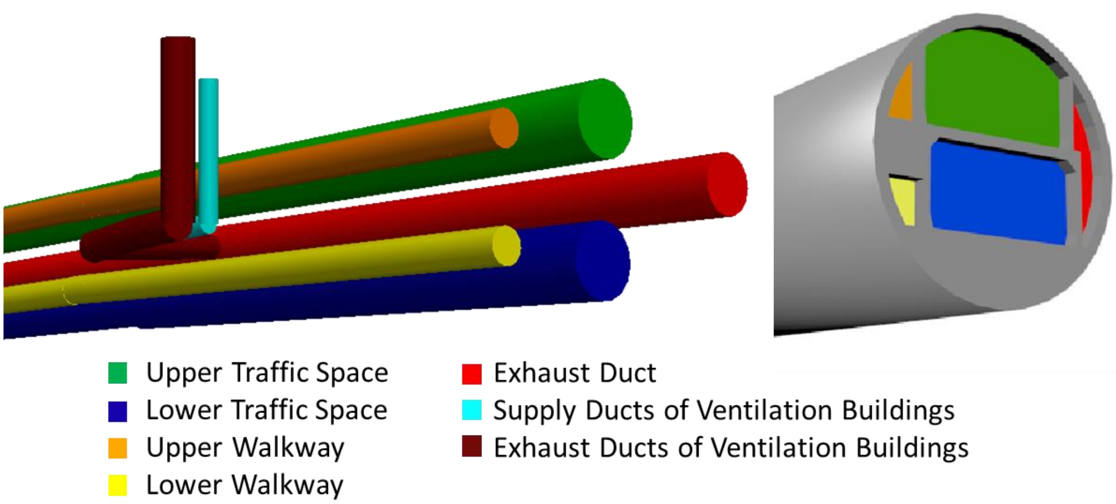


Figure 3-5: Simulation Model, Cut and Cover Section South

The visualizations of the simulation results in this chapter contain white arrows. These white arrows mark the flow direction of the air. Black arrows mark the main work direction of the jet fans. The numbers in the figures (e.g.

826,500 cfm) quantify the flow rate. Tunnel parts which are not relevant for the investigated operation mode are illustrated grey and transparent.

3.5.1 Dimensioning of the Jet Fans

According to the fresh air requirements, the highest fresh air flow rate, which is necessary at a collective vehicle speed of 37.5 mph(3,300 fpm), is about 826,000 cfm. This flow rate is equivalent to an air velocity of 1,325 fpm in the lower TBM traffic area. In this case the vehicle speed is higher than the air velocity and therefore the vehicles assist the airflow in the tunnel.

Another maximum point of necessary fresh air occurs at a vehicle speed of 12.5 mph(1,100 fpm) and is about 793,000 cfm, which is equivalent to an air velocity of 1,270 fpm in the lower TBM traffic area. In this scenario the vehicle speed is lower than the air velocity and therefore the vehicles constitute an obstacle to the air flow. Hence the flow rate of 793,000 cfm and the collective vehicle velocity are relevant for the dimensioning of the jet fans.

3.5.2 Normal Operation Simulation, Lower Deck

Since the cross section of the lower decks traffic area is smaller than the cross section of the upper decks traffic area in the TBM section, the same flow rate causes a higher air velocity and therefore a higher pressure loss in the lower traffic area. Hence proper ventilation of the lower deck is more critical at normal operation than proper ventilation of the upper driving deck. Therefore the amount and size of the jet fans is determined first for the lower deck.

Within this chapter southbound traffic in the lower driving deck is assumed, because of the higher portal pressure difference compared to northbound traffic. The tunnel air is extracted from the lower decks traffic area at the Ventilation Building South. The supply fans in both ventilation buildings are not operating. A portal pressure difference of 0.66 in.wg has been defined at the South Portal and counteracts to the tunnel ventilation. Jet fans with a thrust of 625 lbf are situated in pairs in the lower decks traffic area. (This portal pressure difference is the result of the meteorological analysis of weather stations in LA Downtown, Burbank, El Monte. See section. 2.2 for details.)

The traffic density during a weekday at AM Peak Period (6-9 AM) has been used. The driving speed is 12.5 mph, because the fresh air requirement at this speed is high and the hydraulic resistance at this speed is also high.

Figure 3-6 shows simulation results for the pressure difference in the lower decks traffic space. The simulation showed that a minimum number of 18 jet fans is necessary to reach the required fresh air flowrate. Four jet fan pairs are situated in the C&C cross section of the Ventilation Building South and five pairs are situated in the C&C cross section of the Ventilation Building North.

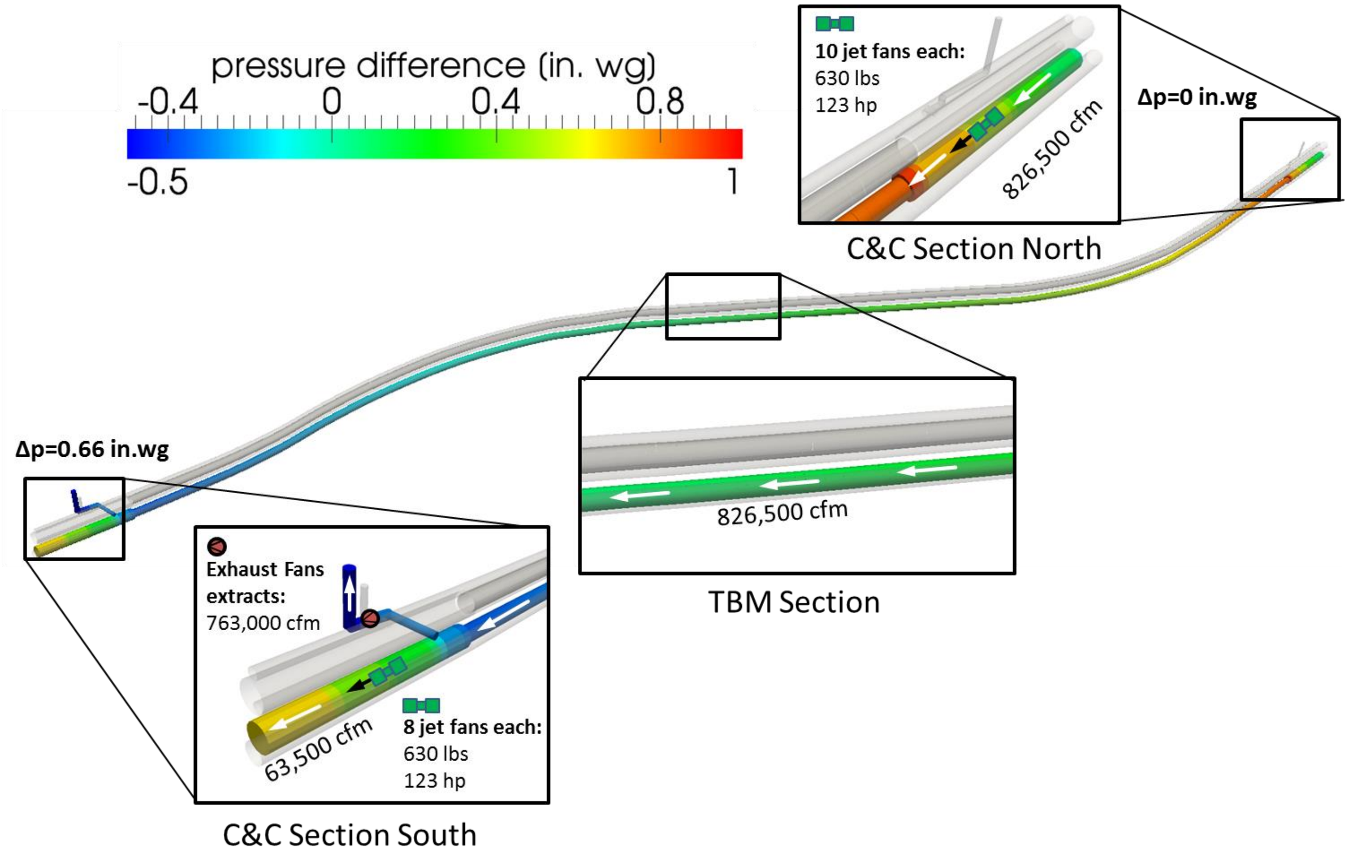


Figure 3-6: Pressure Difference for Normal Operation in the Lower Decks Traffic Space, Southbound Traffic

The pressure difference along the lower decks traffic area is illustrated in Figure 3-7. In this figure the air flows from the right side (North Portal) to the left side (South Portal). The portal pressure difference of 0.66 in.wg can be recognized by looking at the right and the left end of the graph. The linearly increasing line in the middle of the graph is caused by wall friction in the TBM section. The sawtooth-profile at the left and the right end of the graph is caused by the pressure rises, which are induced by the jet fans.

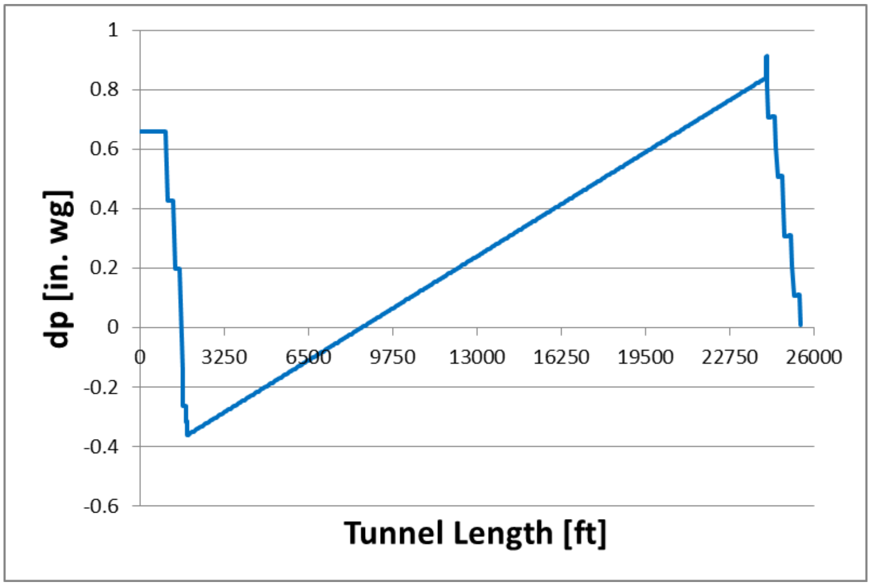


Figure 3-7: Static Pressure in the Lower Decks Traffic Area for Normal Operation

Figure 3-8 shows the results for the flow rate of the simulation. The flow rate of fresh air in the lower decks traffic space is about 826,500 cfm and therefore high enough to fulfill the fresh air requirements. The extracted tunnel air at the Ventilation Building South is about 795,000 cfm.

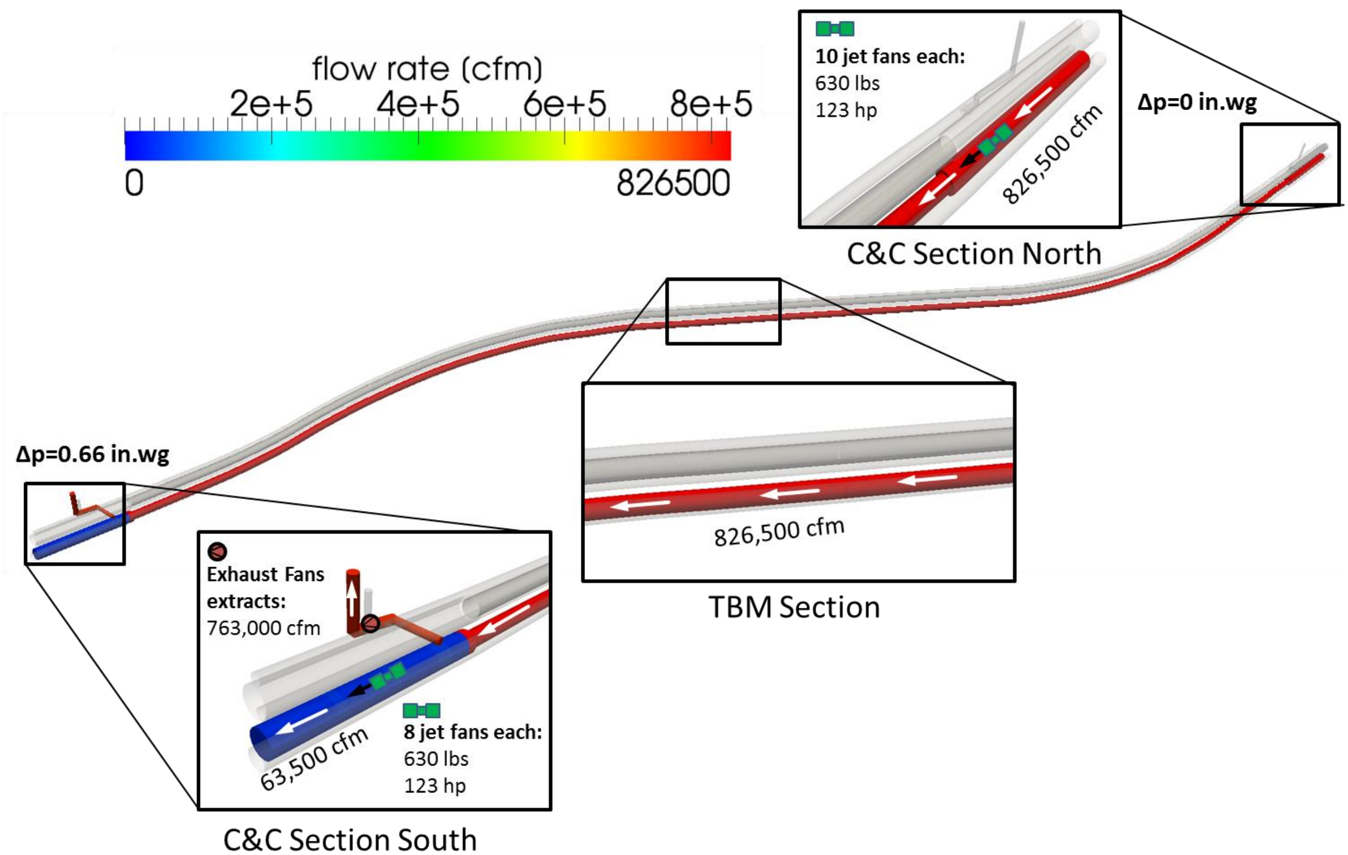


Figure 3-8: Flow Rate for Normal Operation in the Lower Decks Traffic Space, Southbound Traffic

Figure 3-9 illustrates the flow rate along the lower decks traffic area in form of a graph. Since the cross section of the upper decks traffic area is bigger than the lower decks traffic area cross section, a second simulation is necessary to determine the minimum amount of required jet fans for normal operation at the upper deck.

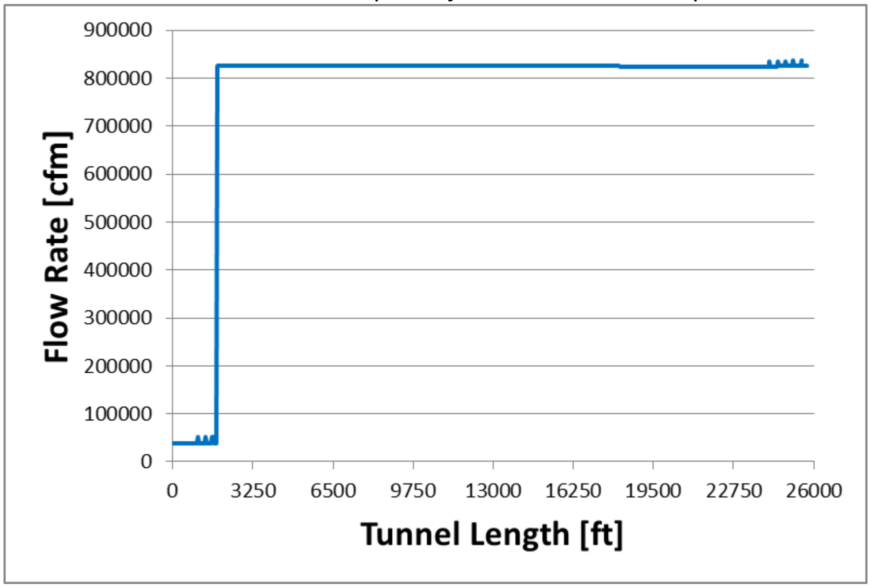


Figure 3-9: Flow Rate in the Lower Decks Traffic area for Normal Operation

3.5.3 Normal Operation Simulation, Upper Deck

Within this chapter the minimum necessary amount of jet fans for proper ventilation of the upper decks driving space is determined. The required fresh air flow rate is the same as for the lower deck, but since the cross section of the traffic area in the TBM section is higher than the lower decks cross section, the pressure loss and therefore the amount of jet fans sink. The tunnel air is exhausted from the upper decks traffic area at the Ventilation Building South, because southbound traffic in the upper driving deck is assumed. Southbound traffic has been assumed because of the higher portal pressure difference compared to northbound traffic. The supply fans in both ventilation buildings are not operating. A portal pressure difference of 0.66 in.wg has been defined at the South Portal and counteracts to the tunnel ventilation. Jet fans with a thrust of 625 lbf are situated in pairs in the upper decks traffic area.

The traffic density during a weekday at AM Peak Period (6-9 AM) has been used.

Figure 3-10 shows simulation results for the pressure difference in the lower decks traffic space. The simulation showed that a minimum number of 14 jet fans is necessary to reach the required fresh air flowrate. Three jet fan pairs are situated in the C&C cross section of the Ventilation Building South and four pairs are situated in the C&C cross section of the Ventilation Building North. The pressure

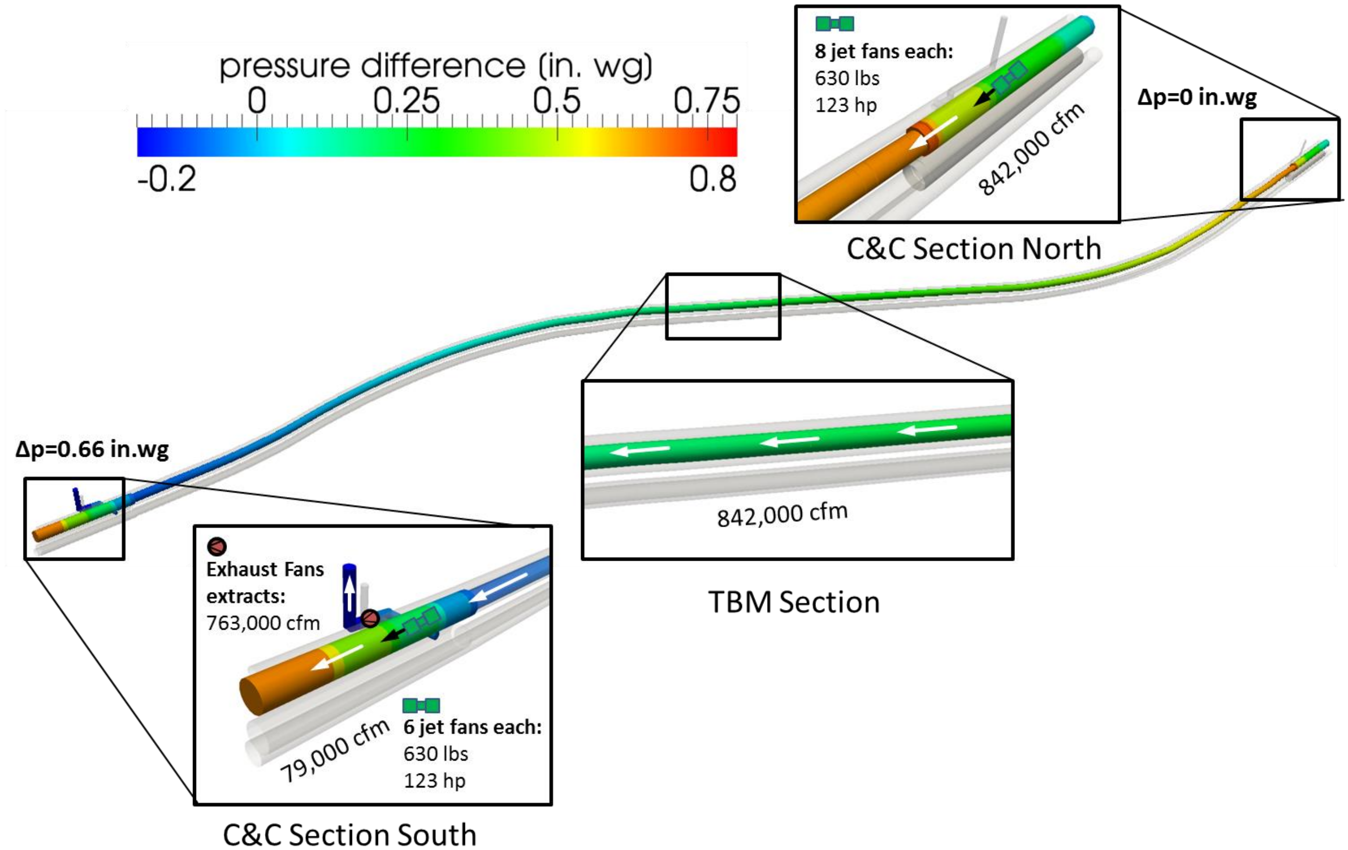


Figure 3-10: Pressure Difference for Normal Operation in the Upper Decks Traffic Space, Southbound Traffic

The pressure difference along the lower decks traffic area is illustrated in Figure 3-11. In this figure the air flows from the right side (North Portal) to the left side (South Portal). The portal pressure difference of 0.66 in.wg can be recognized by looking at the right and the left end of the graph. The linearly increasing line in the middle of the graph is caused by wall friction in the TBM section. The sawtooth-profile at the left and the right end of the graph is caused by the pressure differences, which are induced by the jet fans.

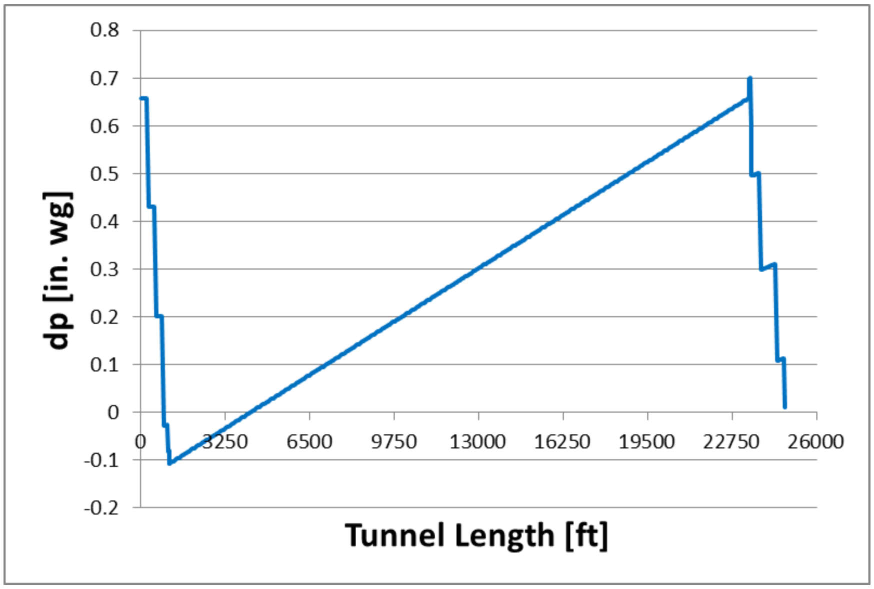


Figure 3-11: Pressure Difference in the Upper Decks Traffic area for Normal Operation

Figure 3-12 shows the results for the flow rate of the simulation. The flow rate of fresh air in the lower decks traffic space is about 842,000 cfm and therefore high enough to fulfill the fresh air requirements. The extracted tunnel air at the Ventilation Building South is about 795,000 cfm.

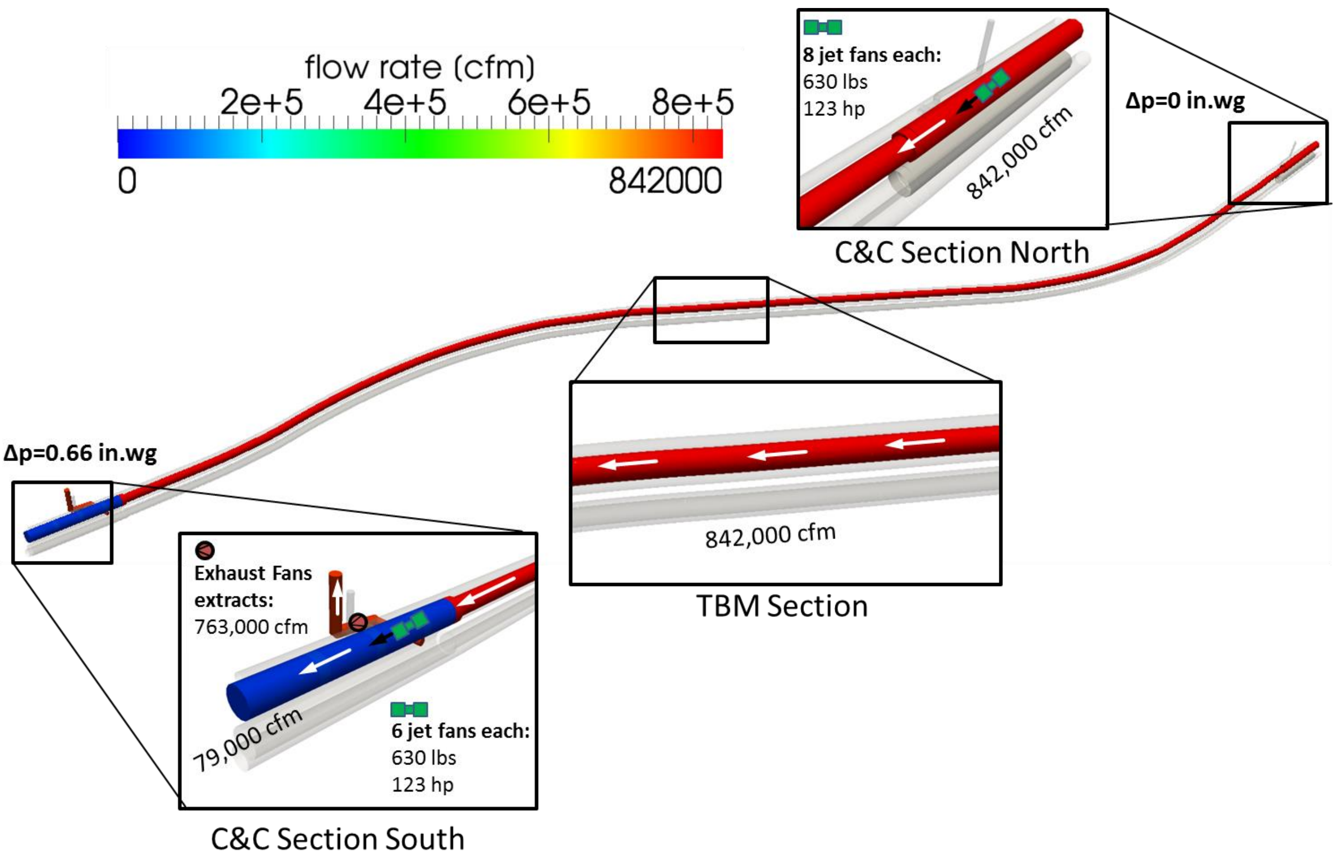


Figure 3-12: Flow Rate for Normal Operation in the Upper Decks Traffic Space, Southbound Traffic

Figure 3-13 illustrates the flow rate along the lower decks traffic area. The flow rate northward of the exhaust gas extraction in the Ventilation Building North is higher than the required flow rate and therefore the ventilation system for normal operation is strong enough to fulfill the fresh air requirements for the ventilation of the upper decks traffic area.

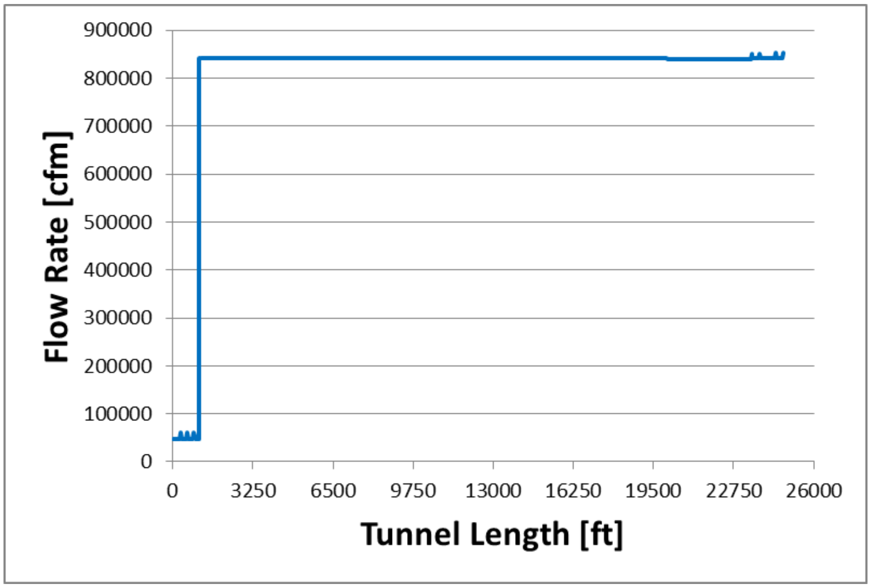


Figure 3-13: Flow Rate in the Lower Decks Traffic area for Normal Operation

3.6 Air Cleaning Equipment

An appropriate design was chosen based on the traffic data for peak hours and the maximum load for the filter devices. The main task of the air cleaning equipment is to filter particles, which are bigger than PM2.5 (Particulate Matter 2.5 µm) out of the tunnel air. A separate air quality study determined that NOX filtering will not be required. Therefore exhaust fumes such as NO and NO_2 will not be removed by the air filtering system.

3.6.1 Technical Data

Figure 3-14 illustrates a single electrical filter for particles.

Figure 3-14: Filter unit [19]

Table 3-11 summarizes the technical data of a single electrostatic precipitator (EP) –unit.

Table 3-11: Technical Data, single EP-unit

Geometry		**High Voltage**		**Properties**	
Width	8 ft - 7 in.	Ionizer	-12 kV	Airflow	63,570 cfm
Height	8 ft – 4 in.	Collector	-6 kV	Pressure loss	0.0232 psi
Weight	4,189 lb			Power consumption	2 hp
				Particle size	0.1 – 20 µm

3.6.2 Performance

A single EP-unit consumes about 2 hp of electrical power to filter an air flow of 63,570 cfm. To cover a volume flow rate of approximately 1,652,000 cfm a power level of approximately 52 hp (approx. 70 kVA) is necessary.

3.6.3 Maintenance of the Air Cleaning Equipment

The cleaning of the EP cells is done by using a fully automatic wash system with flat beam nozzles and an oscillating wash system. Thus the cleaning effect is better than with rigid nozzle systems with lower water pressure at the collector plates. To be able to perform the maintenance a space of 17 ft is required behind the EP unit.

3.6.4 Spacing of Air Cleaning Equipment

Figure 3-15to Figure 3-18 show the spacing of the air cleaning Equipment in the OMC buildings.

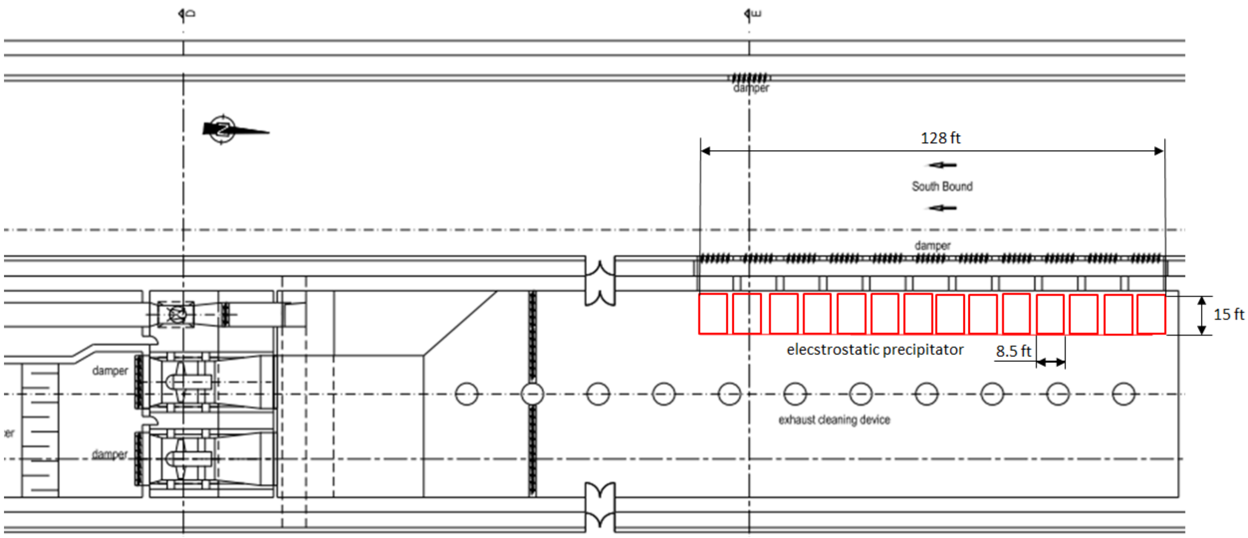


Figure 3-15: Spacing of EP Air Cleaning Equipment, Portal Building South, Plan View

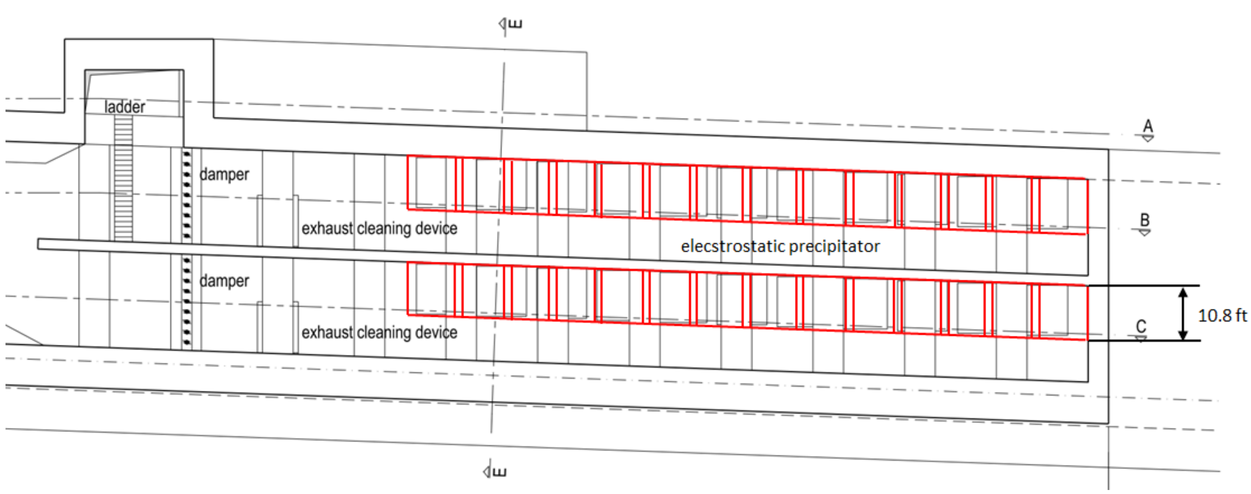


Figure 3-16: Spacing of EP Air Cleaning Equipment, Portal Building South, Longitudinal Section

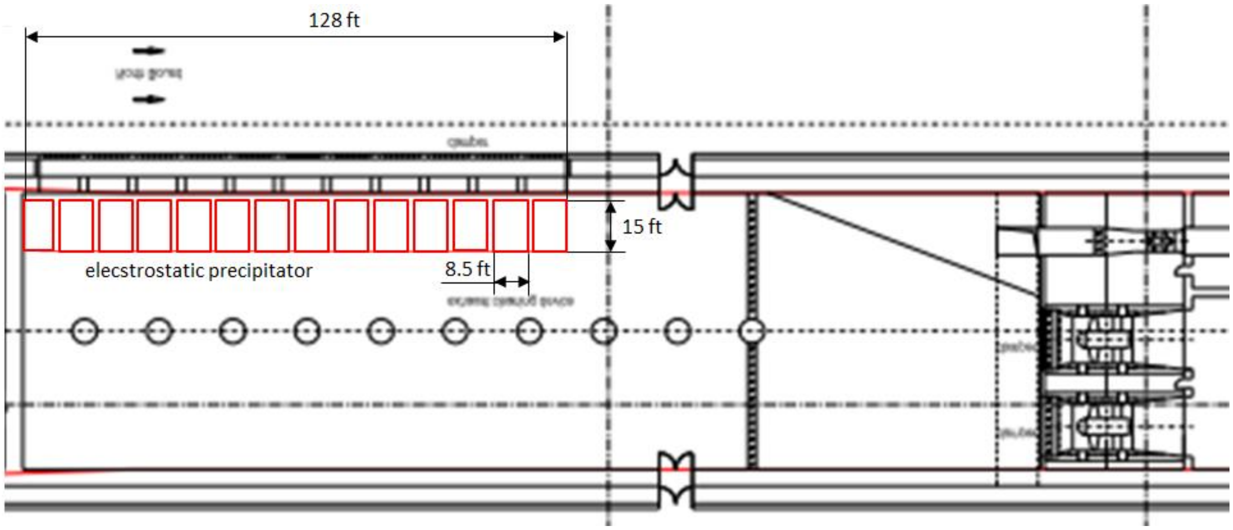


Figure 3-17: Spacing of EP Air Cleaning Equipment, Portal Building North, Plan View

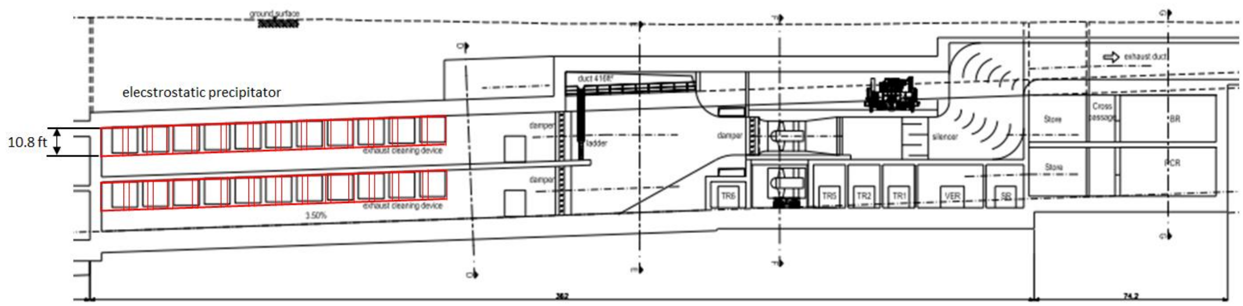


Figure 3-18: Spacing of EP Air Cleaning Equipment, Portal Building North, Longitudinal Section

Ventilation System for Emergency Operation

4.1 Ventilation Concept for Emergency Operation

In the case of a fire in the tunnel, a smoke extraction with dampers every 300 feet ensures that smoke will not spread over a length of more than 600 feet in the tunnel. The two nearest downstream exhaust dampers are opened in order to avoid backlayering. The axial flow fans at both ventilation buildings are activated to extract the smoke from the driving lanes. The shutting dampers between the exhaust duct for emergency operation and the exhaust fans are opened. The hot airflow does not flow through the air scrubbing system and directly flows into the outdoor ambient air.

Figure 4-1 illustrates the emergency ventilation concept for the example of the dual bore alternative. The red parts of the system are used during emergency operation.

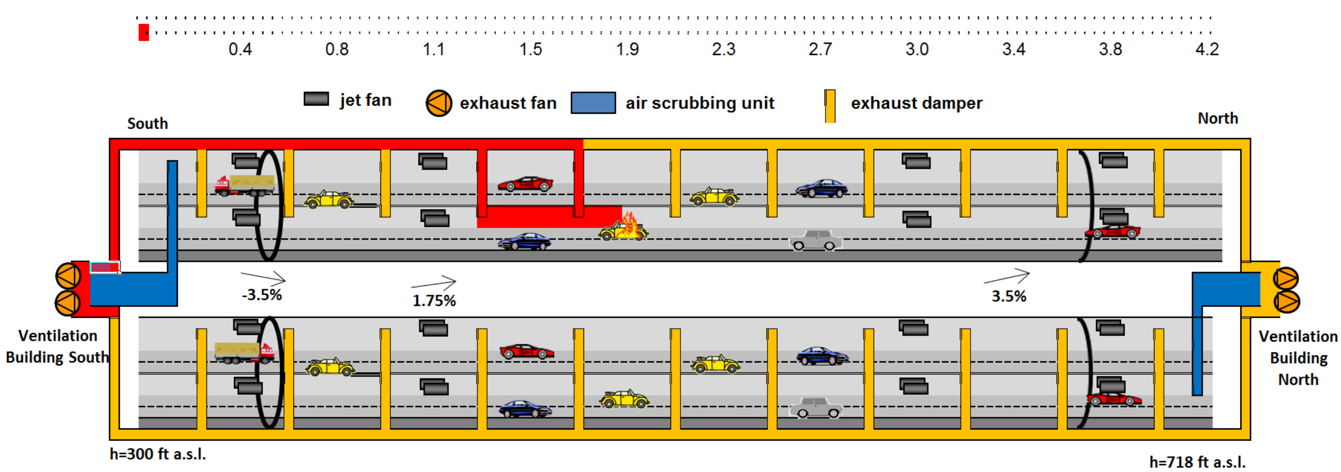


Figure 4-1: Ventilation Concept Scheme, Dual Bore Tunnel

4.2 Pressure Loss in Ventilation Buildings

4.2.1 Pressure Loss in Supply Ducts

The pressure loss for the supply ducts in the ventilation buildings is the same for the single bore and the dual bore alternative. Hence the pressure loss is only pictured once. The required flow rate of the exhaust air fan and supply air fan are simulated using NUMSTA3 for the critical fire scenarios. The air flow rates are used in the following pressure loss calculations. The path of the flowing air can be seen in the Figures of Section 3.6 and 4.4.

Table 4-1: Pressure Loss in Supply Ducts of Ventilation Building South, Emergency Operation

Number	Discription	Values									Remarks and Bibliography
		Cross Section	Perimeter	Hydraulic Diameter	Length	Flow Rate	Velocity	Friction Coefficient	Pressure Loss Coefficient	Pressure Loss	
		[ft²]	[ft]	[ft]	[ft]	[cfm]	[fpm]	[-]	[-]	[in.wg]	
1	Entrance Loss	43.1	26.2	6.6	-	12900	980	-	0.60	0.036	Idel'cik 3.3
2	Air Duct	43.1	26.2	6.6	114.8	12900	980	0.015	0.26	0.016	Wall Friction
3	90° Bend	43.1	26.2	6.6	-	12900	980	-	1.15	0.069	Idel'cik 6.6
4	Air Duct	43.1	26.2	6.6	95.8	12900	980	0.015	0.22	0.013	Wall Friction
5	T-Piece	43.1	26.2	6.6	-	12900	980	-	2.00	0.120	Idel'cik 7.29
6	Air Duct	64.6	32.8	7.9	13.1	12900	660	0.015	0.03	0.001	Wall Friction
7	Entirely Ventilation Unit	-	-	-	-	-	-	-	-	2.113	Efficiency 0.7
8	Silencer	64.6	32.8	7.9	4.9	12900	660	-	-	0.602	Experience Value
9	T-Piece	64.6	32.8	7.9	-	12900	660	-	5.00	0.134	Idel'cik 7.29
10	Air Duct	32.3	26.2	4.9	59.1	12900	1310	0.015	0.18	0.019	Wall Friction
11	T-Piece	32.3	26.2	4.9	-	12900	1310	-	2.00	0.214	Idel'cik 7.29
12	Walkway	60.3	31.7	7.6	12926.4	12900	700	0.015	-	3.750	Wall Friction
13	Buoyancy in Shaft	43.1	26.2	6.6	114.8	12900	980	-	-	0.096	Temperature Difference 68°F
14	Overpressure to Traffic Space	-	-	-	-	-	-	-	-	0.401	
15	Exit Loss	43.1	26.2	6.6	-	12900	980	-	1.00	0.060	Entire Kinetic Energy is Lossed
16	**Sum**	-	-	-	-	-	-	-	-	**7.586**	

Table 4-2: Pressure Loss in Supply Ducts of Ventilation Building North, Emergency Operation

Number	Discription	Values									Remarks and Bibliography
		Cross Section	Perimeter	Hydraulic Diameter	Length	Flow Rate	Velocity	Friction Coefficient	Pressure Loss Coefficient	Pressure Loss	
		[ft²]	[ft]	[ft]	[ft]	[cfm]	[fpm]	[-]	[-]	[in.wg]	
1	Entrance Loss	43.1	26.2	6.6	-	42400	980	-	0.60	0.036	Idel'cik 3.3
2	Air Duct	43.1	26.2	6.6	114.8	42400	980	0.015	0.26	0.016	Wall Friction
3	90° Bend	43.1	26.2	6.6	-	42400	980	-	1.15	0.069	Idel'cik 6.6
4	Air Duct	43.1	26.2	6.6	328.1	42400	980	0.015	0.75	0.045	Wall Friction
5	90° Bend	43.1	26.2	6.6	-	42400	980	-	1.15	0.069	Idel'cik 6.6
6	Air Duct	43.1	26.2	6.6	16.4	42400	980	0.015	0.04	0.002	Wall Friction
7	90° Bend	43.1	26.2	6.6	-	42400	980	-	1.15	0.069	Idel'cik 6.6
8	Air Duct	43.1	26.2	6.6	95.8	42400	980	0.015	0.22	0.013	Wall Friction
9	T-Piece	43.1	26.2	6.6	-	42400	980	-	2.00	0.120	Idel'cik 7.29
10	Air Duct	64.6	32.8	7.9	13.1	42400	660	0.015	0.03	0.001	Wall Friction
11	Entirely Ventilation Unit	-	-	-	-	-	-	-	-	2.193	70% efficiency
12	Silencer	64.6	32.8	7.9	4.9	42400	660	-	-	0.602	Experience Value
13	T-Piece	64.6	32.8	7.9	-	42400	660	-	5.00	0.134	Idel'cik 7.29
14	Air Duct	32.3	26.2	4.9	59.1	42400	1310	0.015	0.18	0.019	Wall Friction
15	T-Piece	32.3	26.2	4.9	-	42400	1310	-	2.00	0.214	Idel'cik 7.29
16	Walkway	60.3	31.7	0.0	11154.7	42400	-	0.015	-	3.750	Wall Friction
17	Buoyancy in Shaft	43.1	26.2	6.6	114.8	42400	980	-	-	0.096	Temperature Difference 68°F
18	Overpressure to Traffic Space	-	-	-	-	-	-	-	-	0.401	
19	Exit Loss	43.1	26.2	6.6	-	42400	980	-	1.00	0.060	Entire Kinetic Energy is Lossed
20	**Sum**	-	-	-	-	-	-	-	-	**7.685**	

4.2.2 Pressure Loss in Emergency Exhaust Ducts

The pressure loss for the emergency exhaust ducts in the ventilation buildings is the same for the single bore and the dual bore alternative. Hence the pressure loss is only pictured once.

Table 4-3: Pressure Loss in Emergency Exhaust Ducts of Ventilation Building South, Emergency Operation

Number	Discription	Values									Remarks and Bibliography
		Cross Section	Perimeter	Hydraulic Diameter	Length	Flow Rate	Velocity	Friction Coefficient	Pressure Loss Coefficient	Pressure Loss	
		[ft²]	[ft]	[ft]	[ft]	[cfm]	[fpm]	[-]	[-]	[in.wg]	
1	Exhaust Duct Parallel to Traffic Space	169,0	75,5	9,0	12926,4	637100	3770	0,015	-	8,350	Wall Friction
2	T-Piece	217,7	89,2	9,8	-	508500	2340	-	5,00	1,695	Idel'cik 7.29
3	90° Bend	514,2	195,5	10,5	-	508500	790	-	1,09	0,043	Idel'cik 6.6
4	50° Rejuvenation	741,0	200,5	14,8	-	508500	690	-	0,07	0,007	Idel'cik 5.23
5	90° Bend	400,8	115,8	13,8	-	508500	1270	-	0,66	0,066	Idel'cik 6.6
6	90° Bend	2126,9	185,0	46,0	-	508500	240	0,000	1,36	0,005	Idel'cik 6.6
7	30° Rejuvenation	2228,7	67,9	131,3	-	508500	230	-	0,04	0,002	Idel'cik 5.23
8	Entirely Ventilation Unit	-	-	-	-	-	-	-	-	4,710	Efficiency 0.7
9	Air Duct	596,0	74,5	32,0	21,7	508500	850	0,015	0,00	0,000	Wall Friction
10	Silencer	596,0	77,8	30,7	-	508500	850	-	-	0,642	Experience Value
11	Air Duct	596,0	81,0	29,4	26,6	508500	850	0,015	0,01	0,001	Wall Friction
12	90° Bend	596,0	84,3	28,3	-	508500	850	-	1,70	0,077	Idel'cik 6.6
13	Air Duct	413,5	87,6	18,9	118,3	508500	1230	0,015	0,09	0,008	Wall Friction
14	Exit Loss	413,5	90,9	18,2	-	508500	1230	-	1,00	0,094	Entire Kinetic Energy is Lossed
15	**Sum**	-	-	-	-	-	-	-	-	**15,700**	

Table 4-4: Pressure Loss in Emergency Exhaust Ducts of Ventilation Building North, Emergency Operation

Number	Discription	Values									Remarks and Bibliography
		Cross Section	Perimeter	Hydraulic Diameter	Length	Flow Rate	Velocity	Friction Coefficient	Pressure Loss Coefficient	Pressure Loss	
		[ft²]	[ft]	[ft]	[ft]	[cfm]	[fpm]	[-]	[-]	[in.wg]	
1	Exhaust Duct Parallel to Traffic Space	169,0	75,5	9,0	12926,4	637100	3770	0,015	-	8,350	Wall Friction
2	T-Piece	230,6	89,9	10,3	-	508500	2340	-	5,00	1,512	Idel'cik 6.6
3	90° Bend	544,4	196,2	11,1	-	508500	790	-	0,55	0,021	Idel'cik 6.6
4	50° Rejuvenation	967,9	205,4	18,9	-	508500	690	-	0,07	0,004	Idel'cik 5.23
5	90° Bend	523,5	120,7	17,3	-	508500	1270	-	0,79	0,046	Idel'cik 6.6
6	90° Bend	2126,9	185,0	46,0	-	508500	240	0,017	1,36	0,005	Idel'cik 6.6
7	30° Rejuvenation	2625,8	67,9	154,7	-	508500	230	-	0,04	0,002	Idel'cik 5.23
8	Entirely Ventilation Unit	-	-	-	-	-	-	-	-	4,639	Efficiency 0.7
9	Air Duct	669,8	74,5	36,0	21,7	508500	850	0,017	0,01	0,000	Wall Friction
10	Silencer	669,8	77,8	34,5	-	508500	850	-	1,90	0,642	Experience Value
11	Air Duct	669,8	81,0	33,1	26,6	508500	850	0,017	0,01	0,000	Wall Friction
12	90° Bend	669,8	84,3	31,8	-	508500	850	-	1,36	0,049	Idel'cik 6.6
13	Air Duct	1148,3	87,6	52,4	13,3	508500	1230	0,017	0,00	0,000	Wall Friction
14	90° Bend	451,1	90,9	19,9	-	508500	1230	-	0,81	0,064	Idel'cik 6.6
15	Air Duct	574,1	94,2	24,4	203,3	508500	-	0,017	0,14	0,007	Wall Friction
16	90° Bend	574,1	97,4	23,6	-	508500	-	-	0,81	0,040	Idel'cik 6.6
17	Air Duct	464,8	100,7	18,5	118,1	508500	-	0,017	0,10	0,007	Wall Friction
18	Exiting Loss	464,8	104,0	17,9	-	508500	-	-	1,00	0,074	Entire Kinetic Energy is Lossed
19	**Sum**	-	-	-	-	-	-	-	-	**15,464**	

4.3 Design Criteria

4.3.1 Heat Release Rate of the Fire

The fire heat release rate (HRR) has been defined to 341,214,163 Btu/hr.

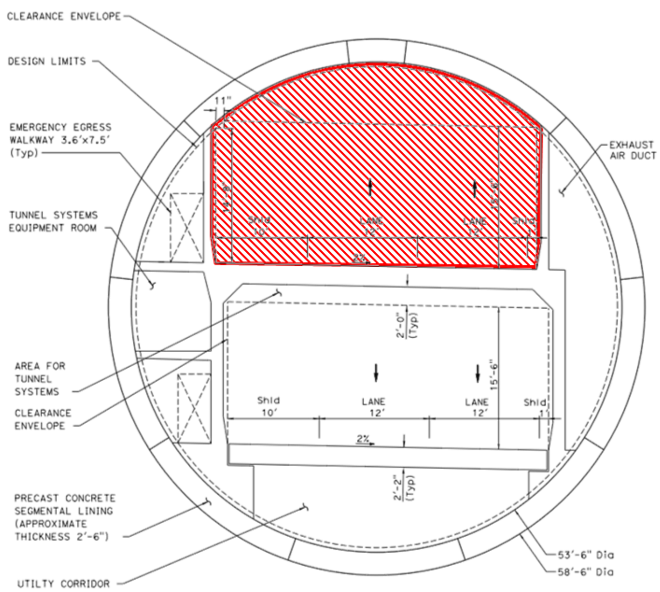
4.3.2 Critical Velocity

The equations of chapter 2.2.1.3 are used for the calculation of the critical air velocity. The most critical case is a negative grade, because the grade factor K_g reaches the highest values in this case. The maximum negative grade in the tunnel system is -3.5%, which causes a grade factor of 1.1 according to FIGURE.D.1 in the NFPA 502 [1].The

HRR of 341,214,163 Btu/hr is used to determine the critical velocity. Since the cross section of the upper, the lower driving decks and the portal buildings are different two separate critical air velocities are calculated.

4.3.2.1 Upper Driving Deck

Figure 4-2 illustrates the cross section of the upper driving deck. The critical air velocity for the geometry of the upper driving deck is 660 fpm.



TYPICAL SECTION

Figure 4-2: Cross Section of the Upper Driving Deck

4.3.2.2 Lower Driving Deck

Figure 4-3 illustrates the cross section of the lower driving deck. The critical air velocity for the geometry of the upper driving deck is 610 fpm.

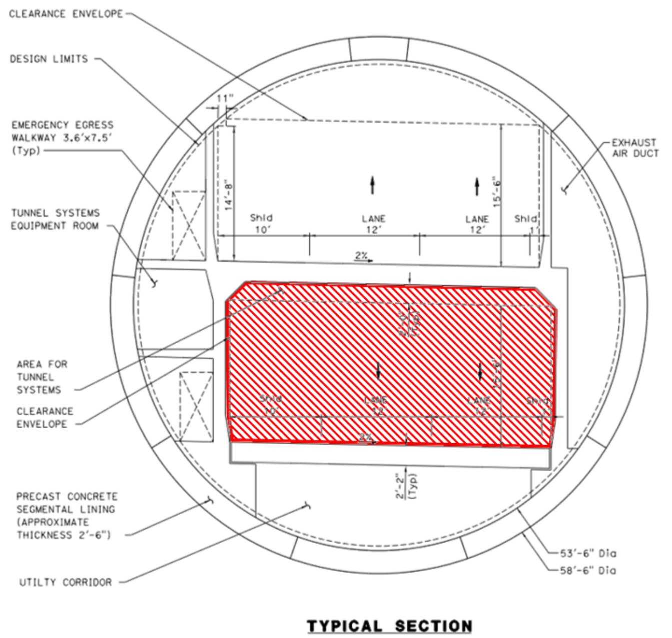


Figure 4-3: Cross Section of the Lower Driving Deck

4.3.2.3 Portal Buildings

Figure 4-4 illustrates the cut-and-cover cross section. The geometry of all four driving decks is the same and therefore their critical air velocity has the same value of 590 fpm.

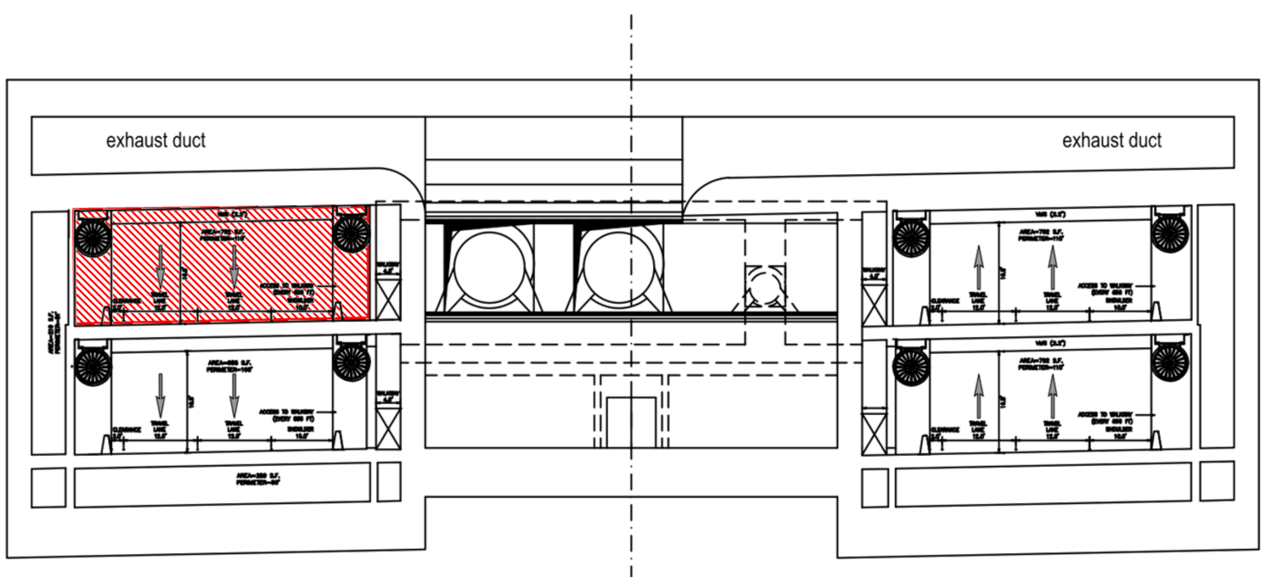


Figure 4-4: Cut-And-Cover Cross Section

4.3.3 Exhaust Flow Rates

In order to meet the NFPA velocity criteria, a certain exhaust flow rate is necessary. This exhaust flow rate depends on the location of the fire and the geometry of the cross sections. The highest exhaust flow rate is necessary when a fire is located at the upper driving deck in one of the ventilation buildings. The scenario of the highest necessary exhaust flow rate is illustrated schematically in Figure 4-5.

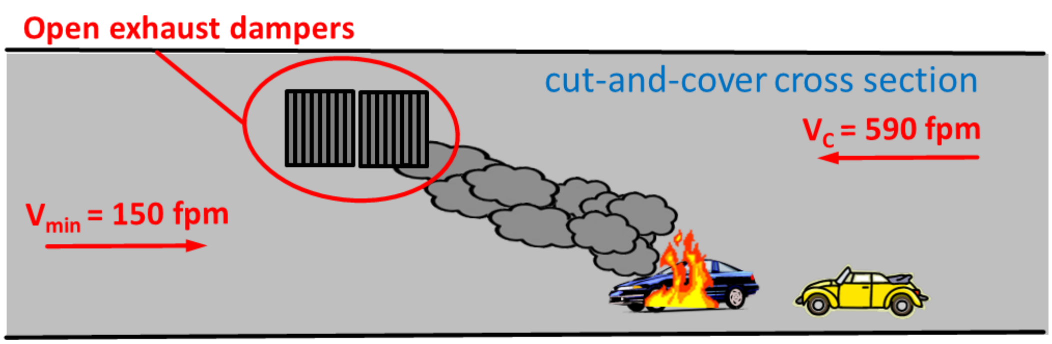


Figure 4-5: Scenario of the Highest Necessary Exhaust Flow Rate

The necessary cool exhaust flow rate for this scenario can be calculated using Equation (1) and is 674,000 cfm.

$$\dot{V}_{cool} = A_{C\&C} * (V_C + V_{min}) \qquad (1)$$

$\dot{V}_{cool}$	cool exhaust flow rate	cfm
$A_{C\&C}$	cut-and-cover cross section	ft^2
V_C	critical air velocity	fpm
V_{min}	minimum necessary velocity	fpm

The cool air is heated by the heat release rate of the fire. To calculate the temperature on the hot side of the fire, following equation is used:

$$T_2 = T_1 + \frac{HRR}{\dot{V}_{cool} * \rho_{cool} * c_p} \qquad (2)$$

T_2	temperature of the hot flow	°F
T_1	temperature of the cool flow	°F
HRR	heat release rate	Btu/hr
$\dot{V}_{cool}$	cool exhaust flow rate	cfm
ρ_{cool}	density of the cool air	lb/ft^3
c_p	Specific heat	J/kg.K

The calculated temperature of the hot exhaust flow rate is 535°F and its density is $2.312*10^{-5}$ lb/ft^3. The hot exhaust flow rate can be calculated using Equation (3) and is 1,270,000 cfm.

$$\dot{V}_{hot} = \dot{V}_{cool} * \frac{\rho_{cool}}{\rho_{hot}} \quad (3)$$

$\dot{V}_{hot}$	hot exhaust flow rate	cfm
ρ_{hot}	density of the hot air	lb/ft^3
$\dot{V}_{cool}$	cool exhaust flow rate	cfm
ρ_{cool}	density of the cool air	lb/ft^3

4.3.4 Used Heat Model

In flow direction the hot air cools down in the exhaust duct (energy transfer from the hot air into the cold tunnel walls). The NUMSTA3 simulation uses the heat model "constant heat transfer" between air and tunnel walls, which is a state of art method for steady state simulations.

4.4 3D CFD Simulations

4.4.1 3D CFD Simulation of the Supply System

This chapter includes 3D CFD simulations of the supply ducts in the ventilation buildings. Since the relatively small cross-sections and the sharp bends of the supply duct could cause high local velocities, the velocity distribution is checked using CFD simulations. Figure 4-6 illustrates the geometry of the simulation model. The ventilation of one walkway is simulated.

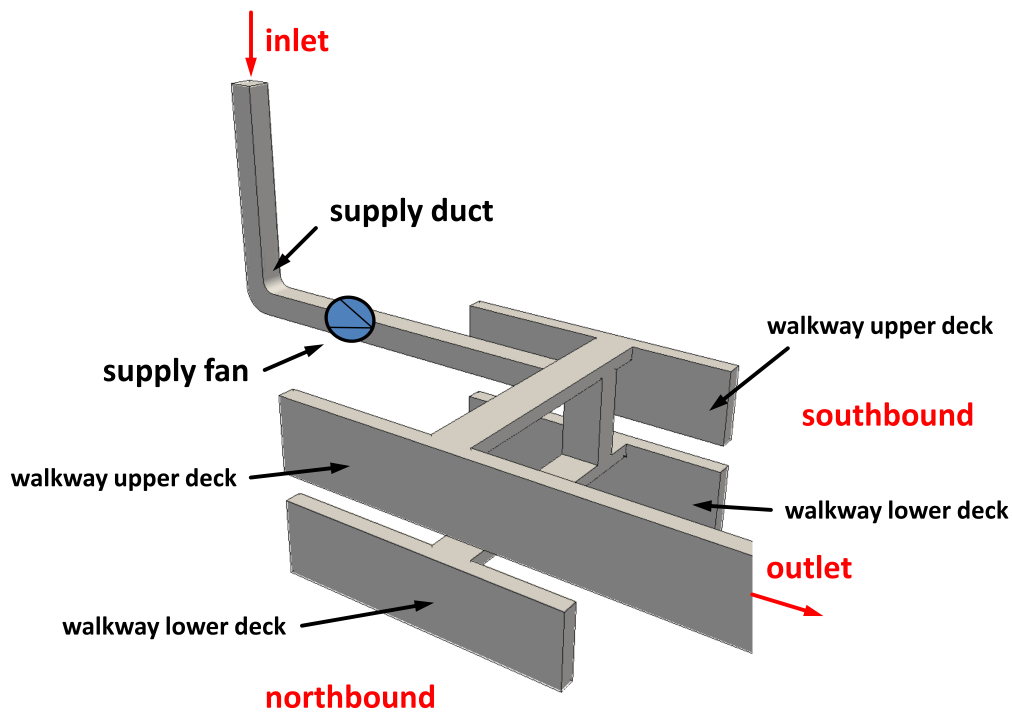


Figure 4-6: Simulation Model of the Supply Ducts in the Ventilation Buildings

A flow rate of 59,000 cfm flows through the system for proper ventilation of the walkways. Figure 4-7 illustrates the path of the air through the supply ducts and the walkway.

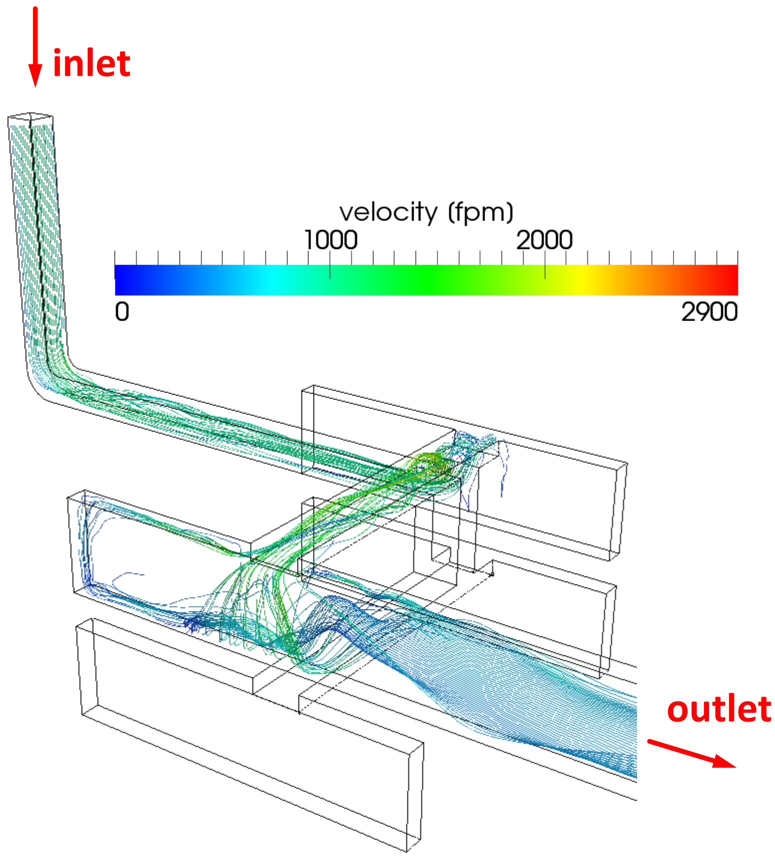


Figure 4-7: Streamlines Through the Geometry

The following Figure illustrates slices through the geometry. The maximum velocity in the ducts is below 4,000 fpm and the average velocity in the walkway is about 950 fpm.

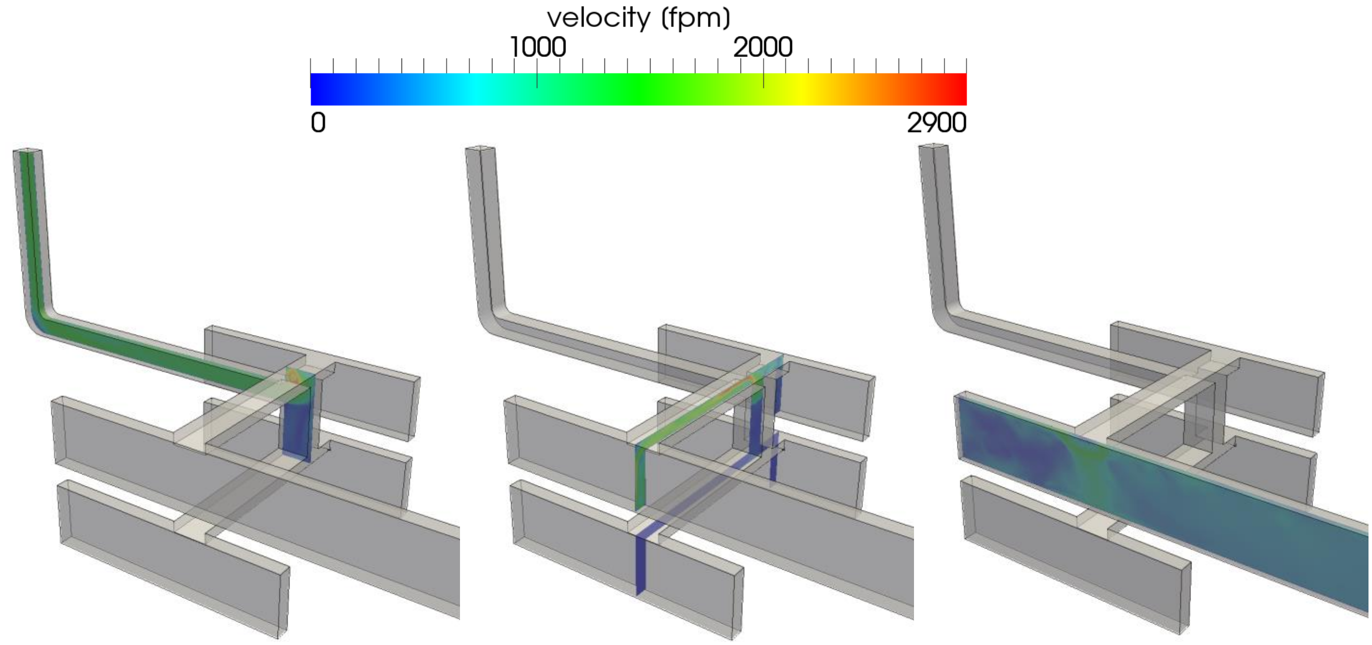


Figure 4-8: Velocity Distribution in the Supply System

4.4.2 3D Simulation of the Emergency Exhaust System

This chapter includes 3D CFD simulations of the emergency exhaust system in the ventilation buildings. High flow rates are necessary to fulfill all criteria of the NFPA 502. These high flow rates cause high pressure losses. The simulation of the ventilation system helps to pin down sources of high local velocities, which cause high pressure losses. Figure 1-1 shows the simulation model of the emergency ventilation system in the ventilation buildings.

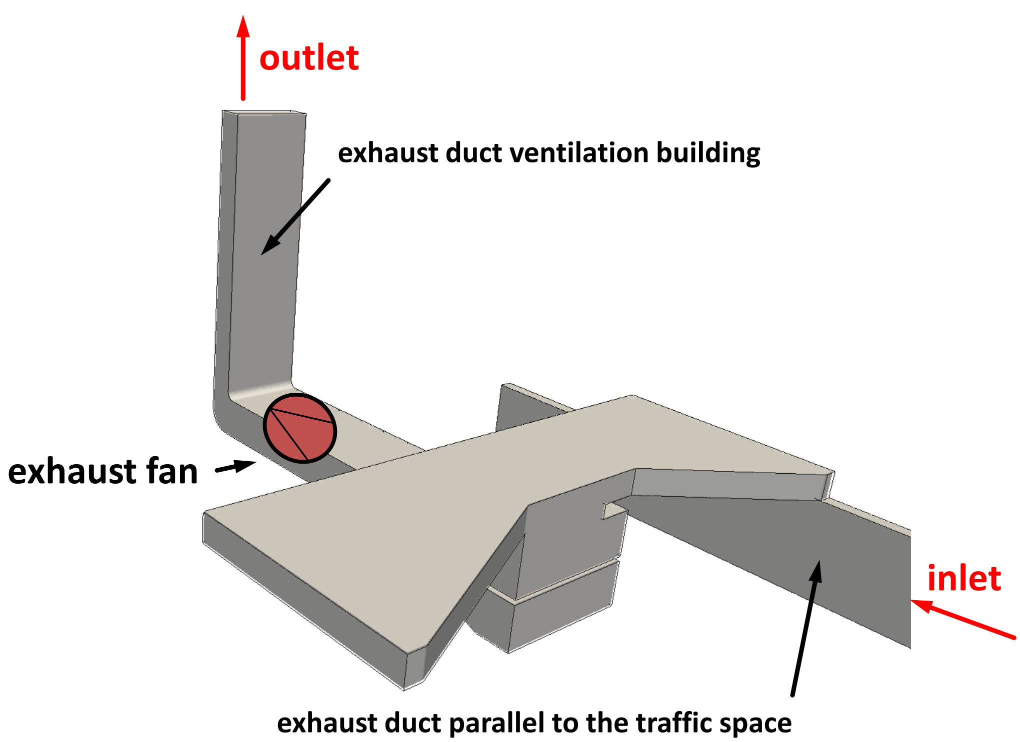


Figure 4-9: Simulation Model of the Emergency Exhaust System in the Ventilation Buildings

A flow rate of 553,000 cfm flows through the system for proper ventilation of the traffic areas in case of an emergency. Figure 4-10 illustrates the path of the air through the emergency exhaust system in the ventilation buildings.

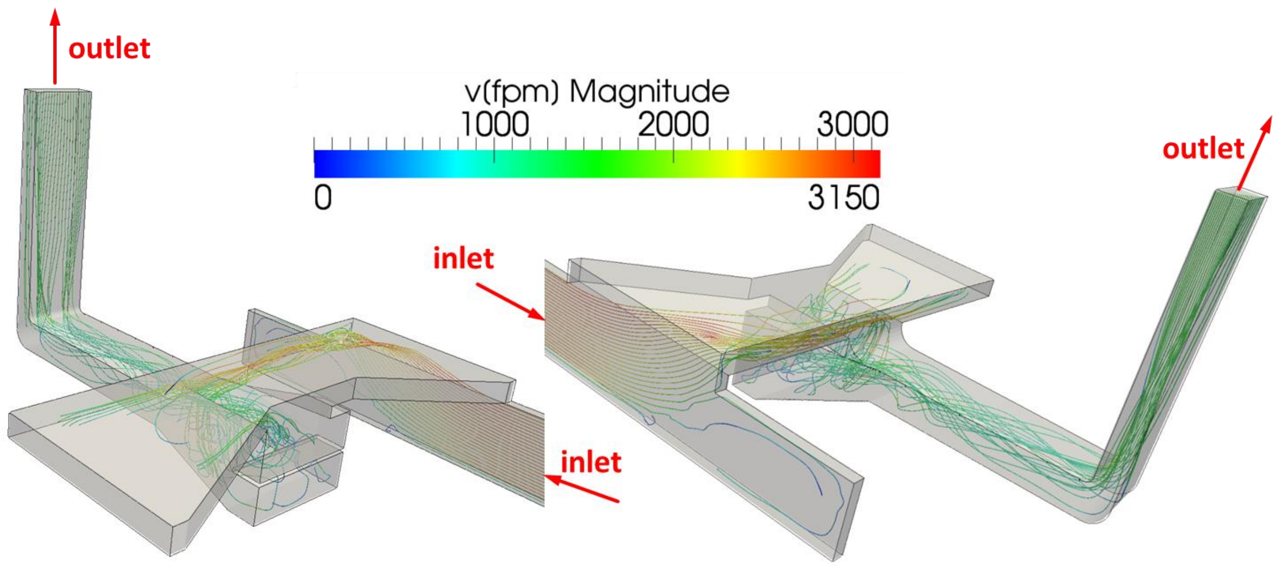


Figure 4-10: Streamlines through the Geometry

The following Figure illustrates slices through the geometry. The maximum velocity in the ducts is about 3150 fpm and occurs in the emergency exhaust duct. The velocities in the ventilation building are at moderate levels and don't require any improvements of the geometry in order to reduce the pressure loss.

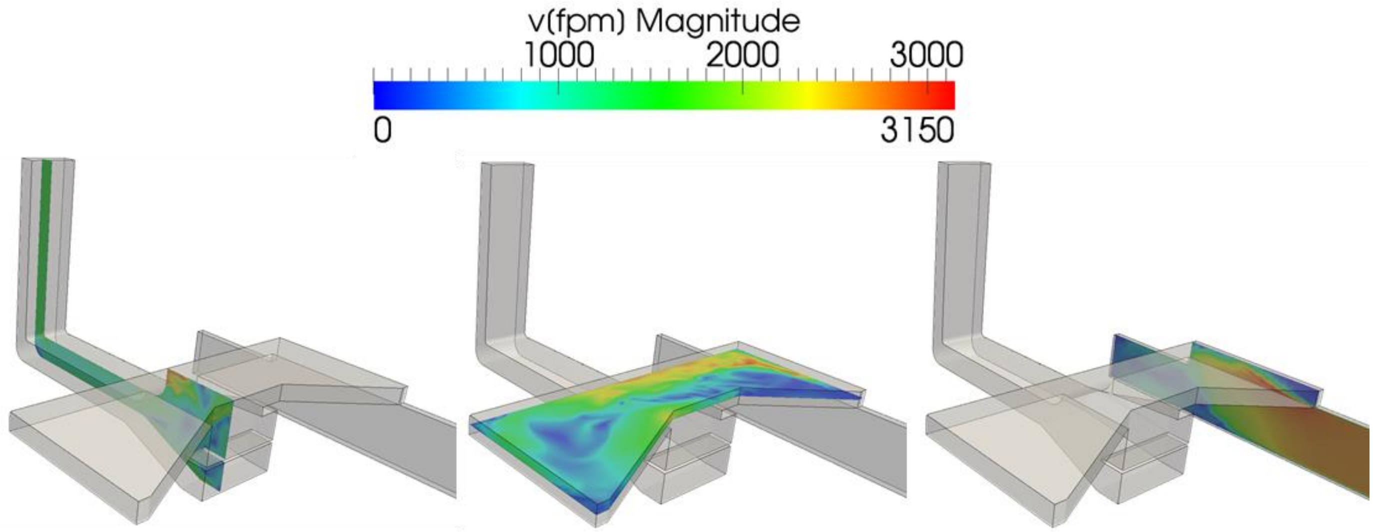


Figure 4-11: Velocity Distribution in the Emergency Exhaust System

4.5 NUMSTA3 Simulations

The visualizations of the simulation results in this chapter contain white arrows. These white arrows mark the flow direction of the air. Black arrows mark the main work direction of the jet fans. The numbers in the figures (e.g. 700 fpm) quantify the air velocity. Tunnel parts which are not relevant for the investigated operation mode are illustrated grey and transparent.

4.5.1 Fire in the Middle of the Tunnel, Single Bore

In this scenario a fire is burning in the middle of the tunnel in the traffic area of the upper deck. The goal of this simulation is to determine whether the exhaust fans and the jet fans are strong enough to fulfill the velocity criteria. Figure 4-12 illustrates the simulated scenario. The emergency ventilation system is running and three escape doors are opened. Northbound traffic is assumed in the upper traffic space for the single bore alternative. Hence cars are standing still southwards of the fire. The smoke is extracted through the two nearest exhaust dampers upstream of the fire. The jet fans in the C&C sections will be used to regulate the air velocities in the traffic space.

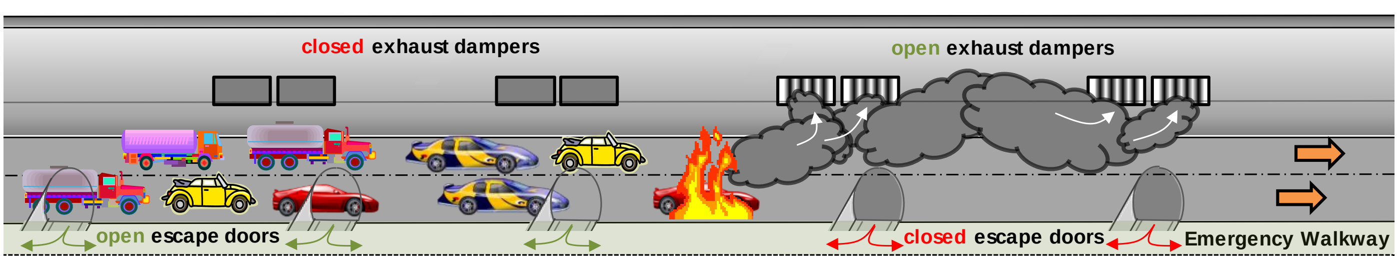


Figure 4-12: Scenario of a Fire in the Upper Traffic area and Open Escape Doors

Figure 4-13 shows the results for the velocity. The critical air velocity of 660 fpm can be reached in the affected tube. The necessary velocity of 150 fpm downstream of the fire also can be reached. To reach these velocities the jet fans are operating northbound. It is not necessary to extract the maximum exhaust flow rate that has been calculated in chapter 4.3.3, because the TBM cross section is smaller than the C&C cross section.

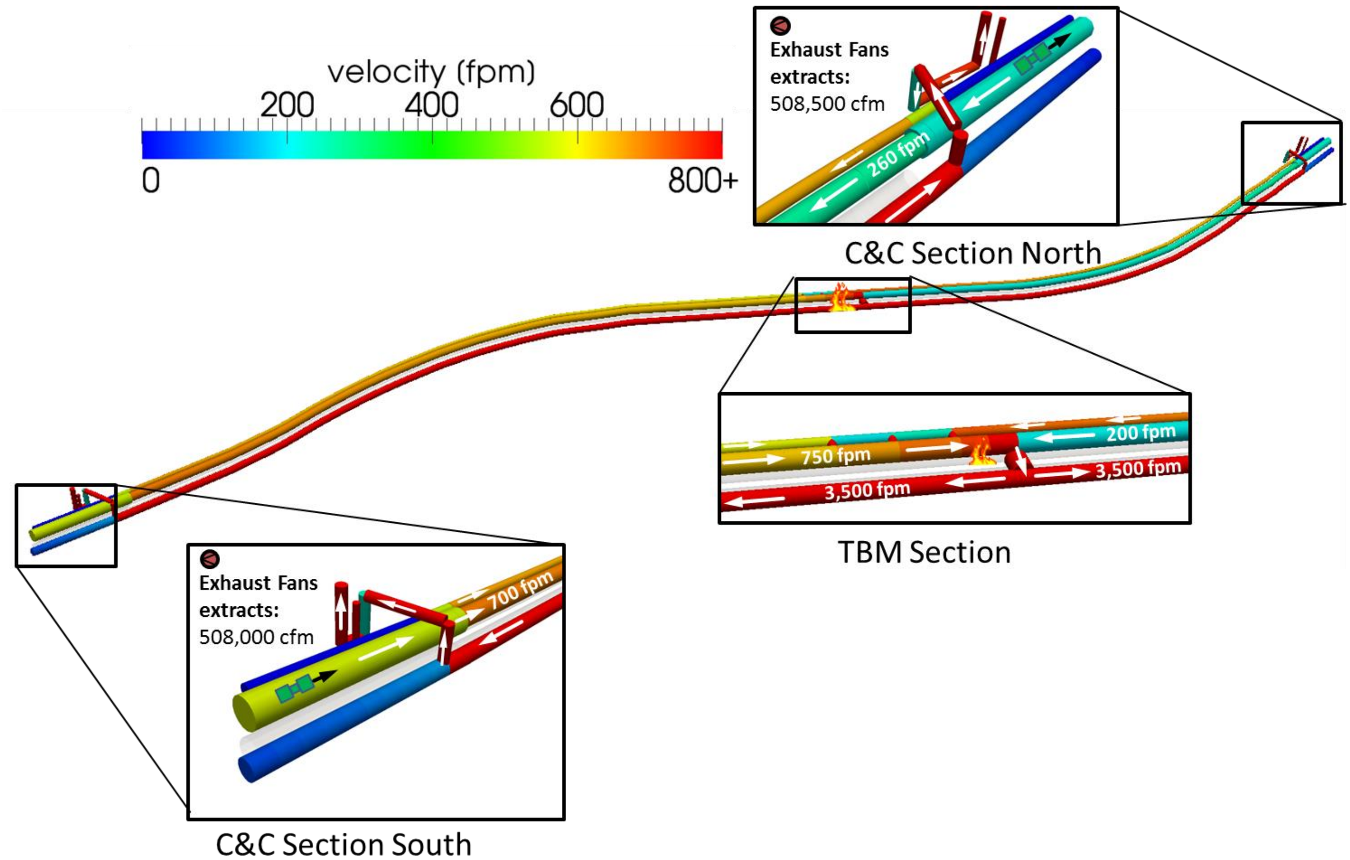


Figure 4-13: Simulation Results for a Fire in the Middle of the Tunnel, Velocity

Figure 4-14 shows that the temperature only rises between the fire and the nearest damper downstream of the fire. The air temperature in the rest of the traffic space can be kept at a low level.

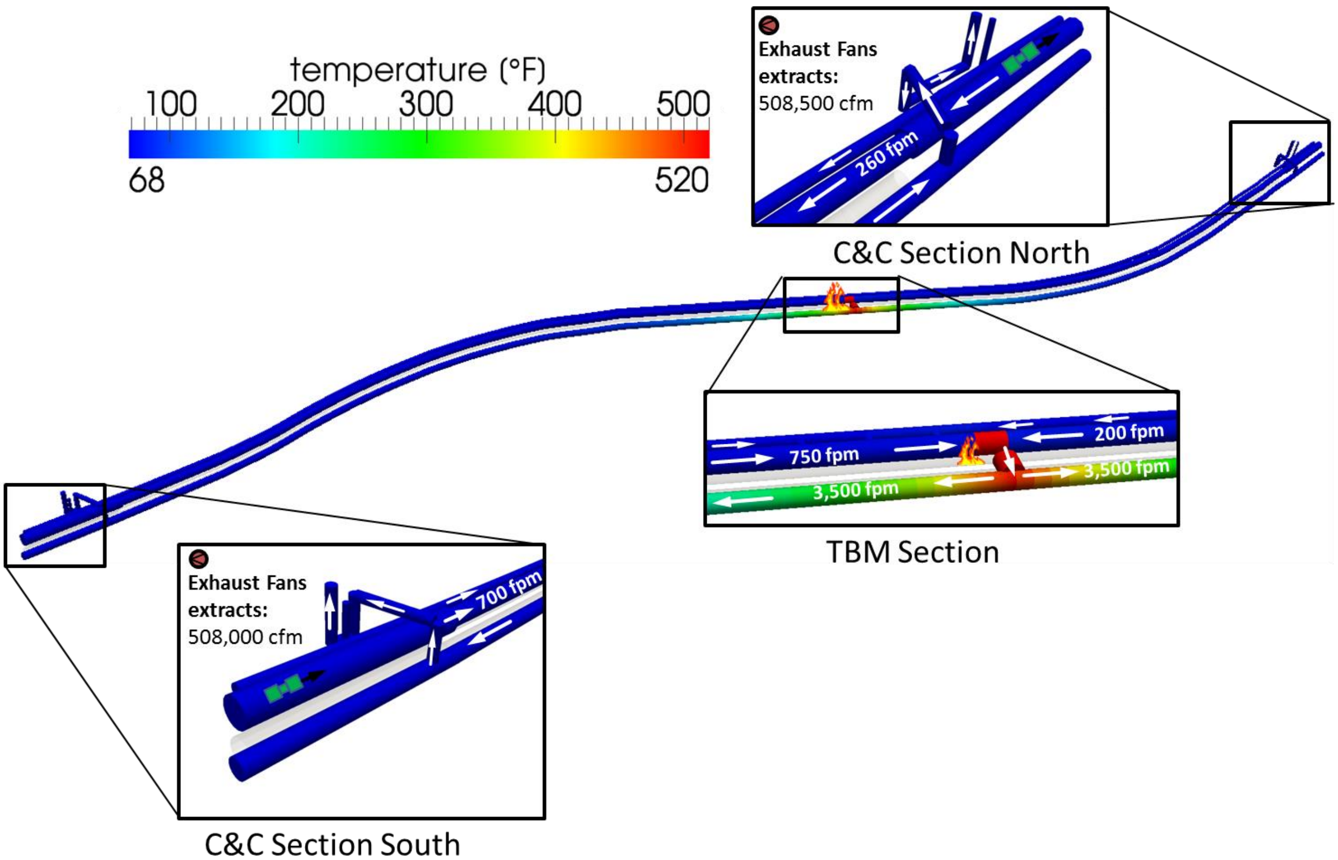


Figure 4-14: Simulation Results for a Fire in The Middle of the Tunnel, Temperature

4.5.2 Fire in the Middle of the Tunnel, Dual Bore

In this chapter the scenario of a fire in the middle of the dual bore alternative tunnel is simulated. The fire is situated in the upper traffic space of the southbound tube. The ventilation system in the southbound tube behaves as in the case of a fire in the single bore tunnel. Additionally one vehicle cross passage is opened to enable fire fighting for the fire brigade. The jet fans in the non-affected tube are keeping the static pressure in traffic space of the non-affected tube at a higher level than the pressure in the traffic space of the affected tube. Because of the pressure difference, backlayering from the affected into the non-affected tube is prevented. Figure 4-15 schematically shows the simulated scenario.

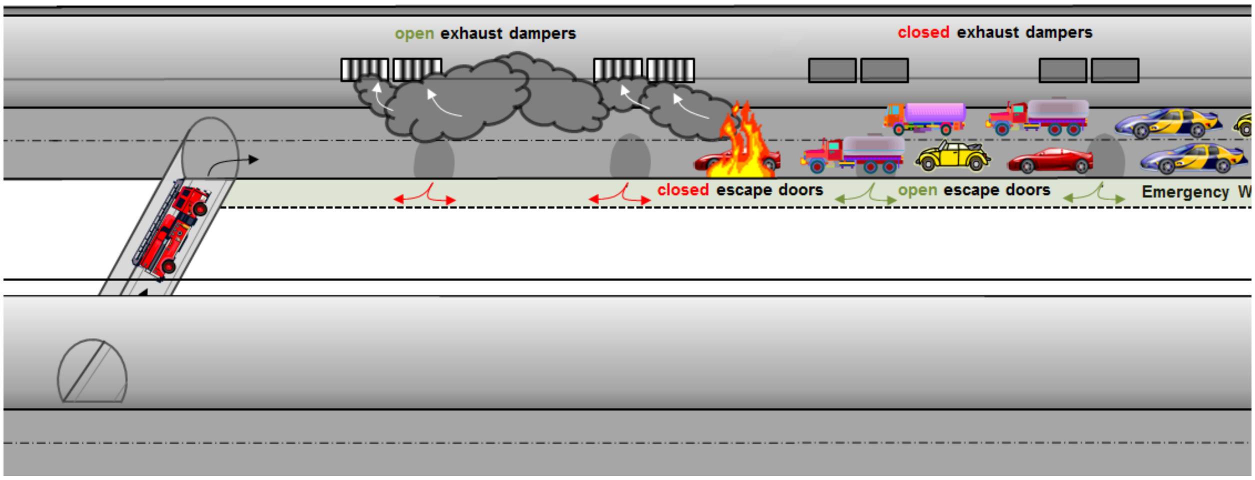


Figure 4-15: Scenario of a Fire in The Middle of the Tunnel, Dual Bore

The simulation results are illustrated in Figure 4-16. Only the upper traffic spaces and the vehicle cross passage are illustrated to keep the figure clear. All jet fans are operating southbound. This way the velocity criteria in the affected tube can be fulfilled and the static pressure of the non-affected tube can be kept at a higher level.

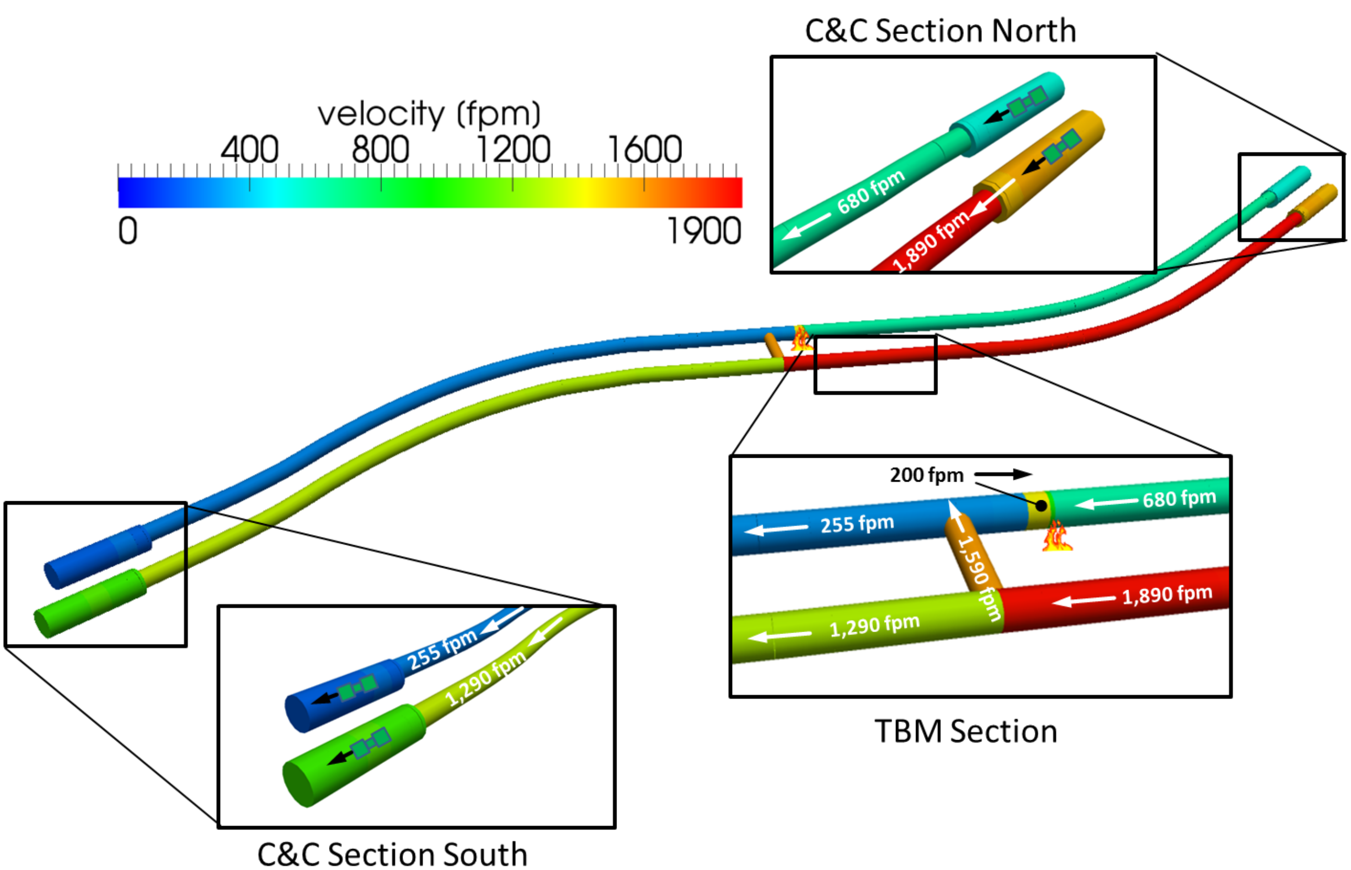


Figure 4-16: Simulation results for a Fire in The Middle of a Dual Bore Tunnel Tube, Velocity

Ventilation Equipment

5.1 Jet Fans

5.1.1 Jet Fan Data

For both, single-bore and dual-bore tunnel on type of jet fan is defined. The jet fan is not 100% reversible. The thrust in the main blow direction is given in the following table.

Table 5-1: Jet Fan data

Jet fan	
Shaft power	130 hp
Thrust	630 lbf
Approximate length	16.4 ft
Approximate outer diameter	5 ft
Approximate rotor diameter	4 ft

The main blow direction is oriented in driving direction. The jet fans are made of stainless steel. The jet fans shall be capable of operating in an ambient temperature of 752 F for a minimum of 90 minutes.

5.1.2 Spacing of the Jet Fans

South bound / Upper deck / **Dual Bore**			
	Tunnel segment	[ft]	Distance to north portal [ft]
North portal	NSBT	1,737+28.70	
jet fan 1 (2x)	NSBT	1,733+61	368
jet fan 2 (2x)	NSBT	1,730+36	693
jet fan 3 (2x)	NSBT	1,727+11	1,018
jet fan 4 (2x)	NSBT	1,723+86	1,343
jet fan 5 (2x)	SSBT	1,455+69	23,959.7
jet fan 6 (2x)	SSBT	1,452+87	28,241.7
jet fan 7 (2x)	SSBT	1,450+05	24,523.7
South portal	SSBT	1,446+75	
South bound / Lower deck / **Dual Bore**			
	Tunnel segment	[ft]	Distance to north portal [ft]
North portal	NSBB	1,739+80	
jet fan 1 (2x)	NSBB	1,736+87	293
jet fan 2 (2x)	NSBB	1,733+62	618
jet fan 3 (2x)	NSBB	1,730+37	943
jet fan 4 (2x)	NSBB	1,727+12	1,268
jet fan 5 (2x)	NSBB	1,723+87	1,593
jet fan 6 (2x)	SSBB	1,451+64	24,616
jet fan 7 (2x)	SSBB	1,448+81	24,899
jet fan 8 (2x)	SSBB	1,445+98	25,182
jet fan 9 (2x)	SSBB	1,443+15	25,465
South portal	SSBB	1,440+35	
North bound / Upper deck / **Dual Bore**			
	Tunnel segment	[ft]	Distance to south portal [ft]
South portal	SSBT	1,446+70	
jet fan 1 (2x)	SSBT	1,450+03	333
jet fan 2 (2x)	SSBT	1,452+86	616
jet fan 3 (2x)	SSBT	1,455+69	899
jet fan 4 (2x)	SSBT	1,458+52	1,182
jet fan 5 (2x)	NSBT	1,727+44	23,874
jet fan 6 (2x)	NSBT	1,730+59	24,189
jet fan 7 (2x)	NSBT	1,733+74	24,504
North portal	NSBT	1,737+28.70	
North bound / Lower deck / **Dual Bore**			
	Tunnel segment	[ft]	Distance to south portal [ft]
South portal	SSBB	1,436+15	
jet fan 1 (2x)	SSBB	1,438+95	280
jet fan 2 (2x)	SSBB	1,441+78	563
jet fan 3 (2x)	SSBB	1,444+61	846
jet fan 4 (2x)	SSBB	1,447+44	1,129
jet fan 5 (2x)	SSBB	1,450+27	1,412
jet fan 6 (2x)	NSBB	1,727+45	24,930
jet fan 7 (2x)	NSBB	1,730+60	25,245
jet fan 8 (2x)	NSBB	1,733+75	25,560
jet fan 9 (2x)	NSBB	1,736+90	25,875
North portal	NSBB	1,739+80	

North bound / Upper deck / **Single Bore**			
	Tunnel segment	[ft]	Distance to south portal [ft]
South portal	SSBT	1,446+70	
jet fan 1 (2x)	SSBT	1,450+03	333
jet fan 2 (2x)	SSBT	1,452+86	616
jet fan 3 (2x)	SSBT	1,455+69	899
jet fan 4 (2x)	SSBT	1,458+52	1,182
jet fan 5 (2x)	NSBT	1,727+44	23,874
jet fan 6 (2x)	NSBT	1,730+59	24,189
jet fan 7 (2x)	NSBT	1,733+74	24,504
North portal	NSBT	1,737+28.70	
South bound / Lower deck / **Single Bore**			
	Tunnel segment	[ft]	Distance to north portal [ft]
North portal	NSBB	1,739+80	
jet fan 1 (2x)	NSBB	1,736+87	293
jet fan 2 (2x)	NSBB	1,733+62	618
jet fan 3 (2x)	NSBB	1,730+37	943
jet fan 4 (2x)	NSBB	1,727+12	1,268
jet fan 5 (2x)	NSBB	1,723+87	1,593
jet fan 6 (2x)	SSBB	1,451+64	24,616
jet fan 7 (2x)	SSBB	1,448+81	24,899
jet fan 8 (2x)	SSBB	1,445+98	25,182
jet fan 9 (2x)	SSBB	1,443+15	25,465
South portal	SSBB	1,440+35	

5.2 Air Duct Equipment

All air duct equipment is made of stainless steel.

5.2.1 Exhaust Dampers

A single extraction point consists of two jalousie exhaust air dampers in a row. One jalousie damper is 8.2 ft wide and 9.8 ft high. Exhaust air dampers are resistant of 752°F during 1 hour.

5.2.2 Shutting Dampers in the Supply Duct

The shutting dampers are jalousie dampers. They are not exposed to high temperatures therefore, not temperature resistance of high temperatures is necessary.

5.2.3 Fresh Air Openings in the Tunnel Wall

The jalousie shutting dampers in the wall between walkway and traffic area are 1 ft wide and 1 ft high. They are located approximately every 3000 ft. During normal operation this shutting dampers are closed. In case of an emergency the dampers open to enable acceptable pressure difference between walkway and traffic are. This concept is suitable for the investigated scenarios but needs to be more detailed during the next design phase.

5.3 Supply Air Fans

Supply fans are located in ventilation building South and North. In case of an emergency the walkway adjacent to the affected deck is ventilated to ensure safe egress. During normal operation the walkways are not ventilated.

Table 5-2: Fan performance of supply air fans

Building	Pressure [in. wg]	Flow Rate [cfm]	Shaft-Power [hp]
OMC South	7.65	42,380	53
OMC North	7.91	42,380	54

Supply fans need no special temperature requirement. The fan will be equipped with a shutoff damper. The efficiency of the fan is considered with 70%.

5.4 Exhaust Air Fans

The exhaust air fans are used for normal operation and in case of an emergency. In case of an emergency the fans are exposed directly to the hot gas stream. Therefore, the fans shall be 100% redundant according to NFPA 502.

The fan performance of the exhaust fans are shown in the following tables.

Table 5-3: Fan performance of exhaust air fans, normal operation, single-bore tunnel

Building	Pressure [in. wg]	Flow Rate [cfm]	Shaft-Power [hp]
OMC South	3.11	762,770	381
OMC North	3.54	826,340	469

Table 5-4: Fan performance of exhaust air fans, normal operation, dual bore tunnel

Building	Pressure [in. wg]	Flow Rate [cfm]	Shaft-Power [hp]
OMC South	4.81	1,525,540	1,172
OMC North	6.52	1,652,670	1,723

Each OMC building has two exhaust air fans because of the 100% required redundancy in case of an emergency. Therefore, during normal operation both exhaust air fans can be used to extract in parallel mode the required flow rate, as listed in Table 5-4. Each fan extracts 50% of it. The shaft-power in Table 5-4 is the sum of both fans.

Table 5-5: Fan performance of exhaust air fans, emergency, fire in middle of tunnel

Building	Pressure [in. wg]	Flow Rate [cfm]	Shaft-Power [hp]
OMC South	15.70	508,520	1,277
OMC North	15.46	508,520	1,258

The fan will be equipped with a shutoff damper. The efficiency of the fan is considered with 70%. The exhaust air fans are equipped with hydraulic powered rotor blade adjustment and a frequency converter. The fans have a temperature resistance of 752°F during 1 hour. The fan will be equipped with a shutoff damper.

In case of a fire the exhaust air fans in OMC building North and South are simultaneously extracting the hot gases. In case of a fire in the middle of the tunnel each fan extracts 50% of the flow rate. When the fire moves towards the portal the closer fan can extract a higher flow rate and the farer fans can extract a lower flow rate. Therefore, the operating point of the fan depends on the distance of the extraction point. The maximum power is necessary for a fire scenario is in the middle of the tunnel.

Additional fire scenarios need to be investigated in order to define a map of operating points over the whole tunnel length. Additional turning vanes in air ducts of the OMC buildings can reduce the pressure losses and therefore, save operating costs during normal operation.

5.5 Tunnel Environmental Monitoring

Various sensors and instrumentation systems will be provided for continual monitoring of critical environmental conditions within the tunnels for health and safety. Signals from the sensor systems will be used as inputs for automated control of the ventilation system. For example, the flow of outside air into the tunnel will be increased by speeding up the exhaust fans. If environmental conditions are outside of prescribed limits, alarms will be triggered through the SCADA system to alert tunnel operators to take appropriate action.

In general, multiple sensors on the roadway will be connected to Air Quality / Air velocity I/O units in the communication rooms. The I/O units are connected to the communications network for transmission of sensor analog data, discrete alarms, and diagnostic functions to the SCADA system (Ventilation PLC).

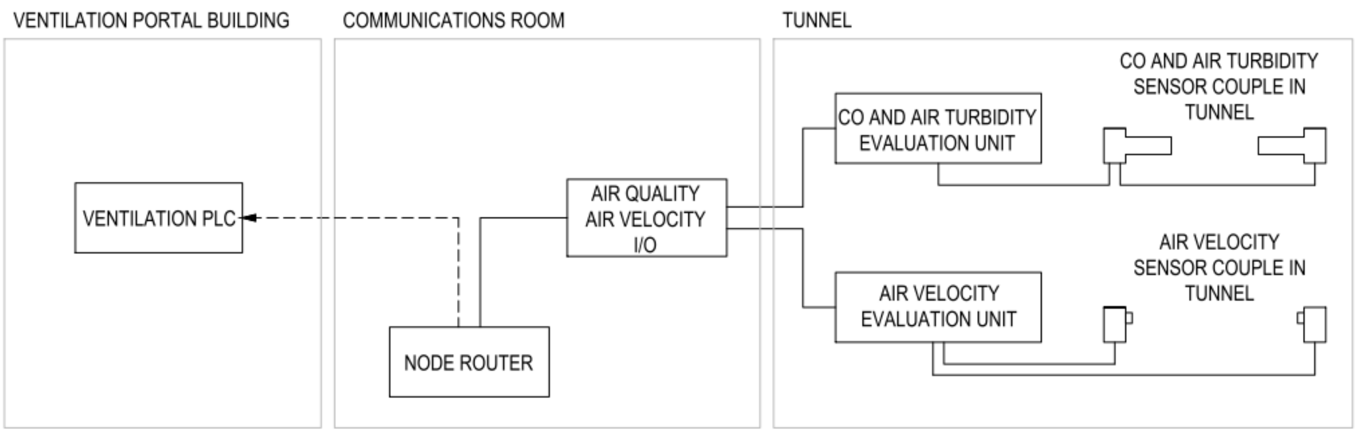


Figure 5-1 Typical Monitoring Configuration

Maintenance requirements for tunnel sensors will be minimized. Sensors will be ruggedized for the harsh tunnel environment and located such that no traffic control is required for access. All instruments, and particularly gas detectors, tend to drift over time, requiring re-calibration. Automated calibration features will be provided in the monitoring system to minimize the cost of field calibrations performed on the roadway.

5.5.1 Carbon Monoxide (CO) Monitoring

Carbon monoxide is the primary toxic gas of concern for monitoring in tunnels. In fact, the potential for hazardous exposure to carbon monoxide is a distinctive criterion for CalTrans for defining a structure as a tunnel. CO sensors will be mounted on the tunnel walls every 300 to 350 feet in both tunnel tubes on both decks. CO concentration will be measured by to detect and alarm concentrations. NFPA 502 (B.2.2) gives the following limits for the CO (values for an altitude up to 984m / 3000ft):

- Maximum of 2000 ppm for a few seconds
- Averaging 1150 ppm or less for the first 6 minutes of the exposure
- Averaging 450 ppm or less for the first 15 minutes of the exposure
- Averaging 225 ppm or less for the first 30 minutes of the exposure
- Averaging 50 ppm or less for the remainder of the exposure

5.5.2 Visibility (Air Turbidity) Monitoring

Visibility in tunnels is affected by particles in the air such as fog, smoke, dust or exhaust fumes. Turbidity sensors determine visibility by measuring the light scattered by these particles. According to the NFPA 502 (B.2.3) the smoke obscuration levels should be continuously maintained below the point at which a sign internally illuminated with a luminance of 8.6 cd/m² (2.5 fl) is discernible at 30 m (100 ft) and doors and walls are discernible at 10 m (33 ft). Turbidity sensors will be co-located with the CO sensors, every 300 to 350 ft in both tunnel tubes on both decks. Certain units may combine monitoring of visibility and CO in a single unit. Certain smoke detectors work by the same principle of light scattering. Although visibility sensors can also be used for early fire detection, separate smoke detectors will be dedicated for fire detection. (See the fire detection section for details.)

Figure 5-2: Turbidity Sensors and Control Unit

5.5.3 Air Velocity Monitoring

Tunnel air velocity is a critical parameter to be controlled, both during normal operation and in the event of a fire.

> NFPA 502 11.2.3 *In tunnels with bidirectional traffic where motorists can be on both sides of the fire site…(2) Longitudinal air velocity shall be kept at low magnitudes.*
>
> NFPA 502 11.2.4 *In tunnels with unidirectional traffic where motorists are likely to be located upstream of the fire site, the following objectives shall be met: (1) Longitudinal systems (a)*Prevent backlayering by producing a longitudinal air velocity that is calculated on the basis of critical velocity in the direction of traffic flow.*

During normal operation, tunnel air velocities produced by the piston effect of traffic are capable of knocking over a person on the shoulder outside of a vehicle. To prevent this hazard, traffic speeds will be reduced and jet fans operated opposite to traffic direction when air velocity is sufficiently high with exposed motorists or personnel on the roadway. According to the NFPA502 (B.2.4) the air velocities in the enclosed tunnel should be greater than or equal to 0.76 m/sec (150 fpm) and less than or equal to 11.0 m/sec (2200 fpm). Air velocity and air flow direction will be measured by ultrasonic sensor couples above the road surface in both tunnel tubes on both decks.

5.5.4 NOx Monitoring

NOx is a relevant parameter for steering the ventilation system during normal operation. The investigations of fresh air requirements showed that NOx is decisive for fresh air volume at low traffic speeds.

5.5.5 Positioning of Tunnel Environmental Monitoring Equipment

In the following tables the position of the air velocity, CO, NOx and visibility meter for the dual and single bore alternative are shown.

Table 5-6: Position of the monitoring equipment; Dual bore; South bound

Dual bore			
South bound / Upper deck			
	Tunnel segment	[ft]	Distance to north portal [ft]
North portal	NSBT	1,737+28.70	
Air velocity 1	NSBT	1,734+34	295
CO/ NOx/ Visibility 1	NSBT	1,732+70	459
Air velocity 2	A	1,654+79	8,250
CO/ NOx/ Visibility 2	A	1,654+79	8,250
Air velocity 3	A	1,571+25	16,604
CO/ NOx/ Visibility 3	A	1,571+25	16,604
CO/ NOx/ Visibility 4	SSBT	1,451+34	24,394.70
Air velocity 4	SSBT	1,449+70	24,558.70
South portal	SSBT	1,446+75	
South bound / Lower deck			
	Tunnel segment	[ft]	Distance to north portal [ft]
North portal	NSBB	1,739+80	
Air velocity 1	NSBB	1,734+34	546
CO/ NOx/ Visibility 1	NSBB	1,732+70	710
Air velocity 2	A	1,654+79	8,501
CO/ NOx/ Visibility 2	A	1,654+79	8,501
Air velocity 3	A	1,571+25	16,855
CO/ NOx/ Visibility 3	A	1,571+25	16,855
CO/ NOx/ Visibility 4	SSBB	1,451+34	24,646
Air velocity 4	SSBB	1,449+70	24,810
South portal	SSBB	1,440+35	

Table 5-7: Position of the monitoring equipment; Dual bore; North bound

Dual bore			
North bound / Upper deck			
	Tunnel segment	[ft]	Distance to south portal [ft]
South portal	SNBT	1,446+70	
Air velocity 1	SNBT	1,449+65	295
CO/ NOx/ Visibility 1	SNBT	1,451+29	459
Air velocity 2	A	1,529+20	4,050
CO/ NOx/ Visibility 2	A	1,529+20	4,050
Air velocity 3	A	1,612+74	12,404
CO/ NOx/ Visibility 3	A	1,612+74	12,404
CO/ NOx/ Visibility 4	NNBT	1,732+65	24,394.70
Air velocity 4	NNBT	1,734+29	24,558.70
North portal	NNBT	1,737+28.70	
North bound / Lower deck			
	Tunnel segment	[ft]	Distance to south portal [ft]
South portal	SNBB	1,439+15	
Air velocity 1	SNBB	1,449+65	1,050
CO/ NOx/ Visibility 1	SNBB	1,451+29	1,214
Air velocity 2	A	1,529+20	4,805
CO/ NOx/ Visibility 2	A	1,529+20	4,805
Air velocity 3	A	1,612+74	13,159
CO/ NOx/ Visibility 3	A	1,612+74	13,159
CO/ NOx/ Visibility 4	NNBB	1,732+65	25,150
Air velocity 4	NNBB	1,734+29	25,314
North portal	NNBB	1,739+80	

Table 5-8: Position of the monitoring equipment; Single bore

Single bore			
Upper deck			
	Tunnel segment	[ft]	Distance to south portal [ft]
South portal	SNB	1,446+70	
Air velocity 1	SNB	1,449+65	295
CO/ NOx/ Visibility 1	SNB	1,451+29	459
Air velocity 2	A	1,529+20	4,050
CO/ NOx/ Visibility 2	A	1,529+20	4,050
Air velocity 3	A	1,612+74	12,404
CO/ NOx/ Visibility 3	A	1,612+74	12,404
CO/ NOx/ Visibility 4	NNB	1,732+65	24,394.70
Air velocity 4	NNB	1,734+29	24,558.70
North portal	NNB	1,737+29.81	
Lower deck			
	Tunnel segment	[ft]	Distance to south portal [ft]
South portal	SNBB	1,439+15	
Air velocity 1	SNBB	1,449+65	1,050
CO/ NOx/ Visibility 1	SNBB	1,451+29	1,214
Air velocity 2	A	1,529+20	4,805
CO/ NOx/ Visibility 2	A	1,529+20	4,805
Air velocity 3	A	1,612+74	13,159
CO/ NOx/ Visibility 3	A	1,612+74	13,159
CO/ NOx/ Visibility 4	NNBB	1,732+65	25,150
Air velocity 4	NNBB	1,734+29	25,314
North portal	NNBB	1,739+80	

Summary

The preliminary design of the normal and emergency ventilation systems for the freeway tunnel alternative of single bore and dual bore was described. Each tunnel tube is approximately 58.5 ft in diameter and 4.9 mi long. Vehicle cross-passages between the bores for emergency use would be provided, nominally spaced every 914 m (3000 ft).

During normal operation at higher speeds the tunnel is self-ventilated by the “piston effect” of the traffic. Under congested traffic conditions, ventilation would be mechanically assisted with jet fans to keep the air quality in the tunnel within required limits for opacity, carbon monoxide and nitrogen oxides. Air scrubbers will filter most of the emission particles. The deposition rate is 90 – 95% of PM_{10} particles and 80 - 85% of $PM_{2.5}$ particles.

In the event of a fire, smoke will be sucked into an exhaust duct via controllable dampers at the fire location and vented from either portal stack. In case of a fire, the ventilation system will provide safe egress in the enclosed and pressurized walkways with emergency exits spaced every approximately 650 ft.

Wind pressure, buoyancy as well as barometric pressure differences between both tunnel portals affect the tunnel ventilation system and therefore, have to be considered in the ventilation design. The measurement stations of LA Downtown, Burbank and El Monte are used for consideration of meteorological influences. The entire pressure difference acting on South portal is 0.66 ín.wg and on North portal is 0.33 in.wg.

The traffic data have been provided for the 1st year of operation (2025) and the 10th year of operation (2035). For the single bore tunnel the annual average daily traffic (AADT) is 89,900 veh/d for a weekday in 2035 incl. 16.7% HGV. For the dual bore tunnel the AADT is 182,200 veh/d for a weekday in 2035 incl. 14.0% HGV. Each tube consists of 4 driving lanes.

For low velocities the NOx-emissions are decisive for the fresh air requirement of about 793,000 cfm. At higher velocities the PM-emissions are decisive for the fresh air requirement of about 826,000 cfm. The Technical Memorandum “Using EMFAC2011 Emission Values as a Basis to Calculate the Fresh Air Requirement” [20] summarizes the input for the fresh air calculation.

Operating vehicles are producing a piston effect. If this piston effect is higher than the meteorological pressure difference, vehicles produce an air velocity in the tunnel. From a certain vehicle speed on, the air velocity is sufficient to achieve the required fresh air flow rate for self-ventilation.

The investigation of self-ventilation shows that the piston effect from operating vehicles is sufficient at speeds above 25 mph to 50 mph. In situations with stop-and-go traffic the minimum speed for self-ventilation depends on the meteorological pressure difference. A mechanical ventilation system is only needed in situations with stop-and-go traffic.

Exhaust air dampers are located every approximately 300 - 350 ft. A single extraction point consists of two jalousie exhaust air dampers in a row. One jalousie damper is 8.2 ft wide and 9.8 ft high. Exhaust air dampers are resistant of 752°F during 1 hour.

The jet fans are made of stainless steel. The jet fans shall be capable of operating in an ambient temperature of 752 F for a minimum of 90 minutes. The thrust in main blow direction is minimum 630 lbf. The jet fan is 4 ft in rotor diameter.

Supply fans are located in ventilation building South and North. In case of an emergency the walkway adjacent to the affected deck is ventilated to ensure safe egress. During normal operation the walkways are not ventilated.

The supply fans are designed with a flow rate of 42,380 cfm and a total pressure rise of about 7.65 (South) and 7.91 (North). Therefore a shaft power of about 54 hp is necessary.

The exhaust air fans are used for normal operation and in case of an emergency. In case of an emergency the fans are exposed directly to the hot gas stream. Therefore, the fans shall be 100% redundant according to NFPA 502.

Fan performance of exhaust air fans, normal operation, single-bore tunnel

Building	Pressure [in. wg]	Flow Rate [cfm]	Shaft-Power [hp]
OMC South	3.11	762,770	381
OMC North	3.54	826,340	469

Fan performance of exhaust air fans, normal operation, dual bore tunnel

Building	Pressure [in. wg]	Flow Rate [cfm]	Shaft-Power [hp]
OMC South	4.81	1,525,540	1,172
OMC North	6.52	1,652,670	1,723

During normal operation both exhaust air fans can be used to extract in parallel mode the required flow rate, as listed in table above. Each fan extracts 50% of it.

Fan performance of exhaust air fans, emergency, fire in middle of tunnel

Building	Pressure [in. wg]	Flow Rate [cfm]	Shaft-Power [hp]
OMC South	15.70	508,520	1,277
OMC North	15.46	508,520	1,258

The efficiency of the fan is considered with 70%. The exhaust air fans are equipped with hydraulic powered rotor blade adjustment and a frequency converter. The fans have a temperature resistance of 752°F during 1 hour. In case of a fire the exhaust air fans in OMC building North and South are simultaneously extracting the hot gases. In case of a fire in the middle of the tunnel each fan extracts 50% of the flow rate.

References

[1] National Fire Protection Association NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways

[2] http://www.aignertunnel.com (03/12/2014)

[3] I.E. Idelchik, Handbook of Hydraulic resistance, 3rd Edition, ISBN 81-7992-118-2

[4] D.S. Miller, Internal Flow Systems, 2nd Edition, ISBN 978-0-9562002-0-4

[5] http://en.wikipedia.org/wiki/Coriolis_effect#Flow_around_a_low-pressure_area (03/19/2014)

[6] PIARC. Road tunnels: Vehicle emissions and air demand for ventilation. PIARC Technical Committee C4. Road Tunnels Operation. Report No. 2012R05EN. PIARC: La Défense, 2012.

[7] US EPA. MOBILE6 Vehicle Emission Modeling Software. http://www.epa.gov/oms/m6.htm

[8] US EPA. MOVES (Motor Vehicle Emission Simulator). http://www.epa.gov/otaq/models/moves/index.htm

[9] CDT. EMFAC Software. http://www.dot.ca.gov/hq/env/air/pages/emfac.htm

[10] California EPA. Air resources board. Mobile Source Emission Inventory -- Current Methods and Data. http://www.arb.ca.gov/msei/modeling.htm

[11] US EPA. Using the MOVES and EMFAC Emission Models in NEPA Evaluations. From: Susan E. Brown. To: NEPA/309 Division Directors, Regions I-X.Date: 10/08/2011. http://www.epa.gov/compliance/resources/policies/nepa/using-the-MOVES-and-EMFAC-emissions-models-in-NEPA-evaluations-pg.pdf

[12] California EPA. Air resources board. Vehicle categories. http://www.arb.ca.gov/msei/vehicle-categories.xlsx

[13] CH2M Hill / J. Emerson. email from 07/30/12. Ref.: "RE: meeting"

[14] California EPA. Air resources board. Air Basin and County Map Boundaries. http://www.arb.ca.gov/desig/adm/basincnty.htm)

[15] Bai, S. D. Eisinger and D. Niemeier. MOVES vs. EMFAC: A comparison of greenhouse gas emissions using Los Angeles County. TRB Annual Meeting, 2009. Revised Version from 11/08/2008.

[16] CH2M Hill / J. Emerson. email from 12/10/12. Ref.: "RE: E574 / vehicle categories from EMFAC"

[17] ASTRA (Swiss Federal Road Authority). Ventilation of Road Tunnels. Guideline No. 13001. V. 2.02 (2008).

[18] Email Company "aigner" to Mr. Mader, subject: Tunnel air cleaning, Fri 21.02.2012

[19] Brochure "aigner, tunnel technology", http://www.aigner.at/

[20] TM, Using EMFAC2011 emission values as a basis to calculate the fresh air requirement, May 6, 2013.

[21] CH2M Hill, Email from Jennifer Martin regarding [SR 710 North] Traffic Data for Ventilation Analysis to Marc Knickerbocker, 19th March 2014