Smoke Management Systems Upgrades for I-90 Tunnels in Seattle

Igor Maevski, PhD, PE
Member ASHRAE, Vice Chair TC5.9, JACOBS

Bob Josephson, PE
JACOBS

Raymond Klein, PE
Member ASHRAE, JACOBS

Yuan Li, PE
Member ASHRAE, JACOBS

Jarrod Alston, PE
Member ASHRA, ARUP

Doug Haight, PE
WSDOT

Zak Griffith, PE
WSDOT

ABSTRACT

WSDOT and Sound Transit are adding high-occupancy vehicle (HOV) lanes to the outer roadways of the I-90 Mt. Baker Ridge and Mercer Island tunnels in both directions. This collaboration will make vital improvements for traffic flow on I-90 while preparing the center roadway for Sound Transit's East Link light rail line from Seattle to Mercer Island, Bellevue and Redmond. The I-90 tunnels were opened to traffic in 1989 with a full transverse ventilation system and 3% AFFF fixed fire suppression system, and the smoke management system improvements for the tunnels are of a vital importance for safe tunnel operation that includes loaded fuel tankers. The design team performed ventilation system tests, suppression system tests, live fire tests, Saccardo nozzle scale modeling tests and CFD analysis to upgrade the existing smoke management systems with minimum construction impact on tunnel operation. The new fire detection system is the key for timely activation of the smoke management systems. Multiple ventilation strategies were adopted to provide an emergency ventilation system capable of addressing smoke and heat from heavy goods or flammable liquids cargo fires including: sectionalization of the existing full transverse ventilation system for the westbound Mt. Baker Ridge tunnel; jet fans for the eastbound Mt. Baker Ridge tunnel and Saccardo nozzles for the Mercer Island tunnels.

INTRODUCTION

The Mount Baker Ridge Tunnel (MBRT) and Mercer Island Tunnel (MIT) are two tunnels of approximately 3,400 feet and 2,900 feet in length, respectively located along Interstate-90 (I-90) in Seattle, WA. Safety, accessibility, and functionality of both the MBRT and MIT are of paramount importance for the Washington State Department of Transportation (WSDOT) and the cities of Seattle and Mercer Island. WSDOT does not restrict fully-loaded fuel tankers and other hazardous cargo that use the tunnels as long as the tunnel fire/life safety systems are fully operational.

WSDOT and Sound Transit are adding high-occupancy vehicle (HOV) lanes to the outer roadways in both directions. This collaboration is making vital improvements for traffic flow on I-90 while preparing the center roadway (currently carrying reversible traffic) for Sound Transit's East Link light rail line from Seattle to Mercer Island, Bellevue and Redmond. The fire & life safety improvements in the I-90 tunnels are of a vital importance for the project.

Tunnel safety, and more explicitly tunnel fire safety, is dependent on the functionality and effectiveness of the fire/life

Igor Maevski is a manager of the Mechanical Department in Jacobs Engineering, New York, NY. Bob Josephson is a Project Manager (Jacobs), Raymond Klein and Yuan Li are Mechanical Engineers (Jacobs, New York), Jarrod Alston is Associate Principal in ARUP, Boston, MA; Doug Haight is a Project Principal with WSDOT (Seattle, WA); Zak Griffith is a Project Manager with WSDOT (Seattle, WA).

safety system, which includes a fire detection system, a 3% Aqueous Film-Forming Foam (AFFF) water based fixed fire suppression system, a tunnel ventilation system, fire alarms, and video surveillance. At the outset of a fire-related incident, timely activation and overall response of these systems are crucial to reacting to an incident quickly and keeping a fire under control.

DESIGN APPROACH

The design and evaluation criteria that have been applied to the evaluation of upgrades for the existing tunnel fire and life safety systems are primarily based on National Fire Prevention Association Standard for Road Tunnel Bridges and Other Limited Access Highways, 2011 Edition (NFPA 502)[2]. The main intent of the standard is to assure the safety of tunnel users during fire emergencies to the best extent feasible. This goal is achieved by providing a tenable environment and supporting safe evacuation.

Considering the type of traffic in the tunnels and the associated risks, the project has established the design fire development curves for both heavy goods vehicle (HGV) and fuel tankers that will use the tunnels. A heavy goods vehicle fire has been determined to have an exponential fire growth curve (ultrafast power-law t squared fire growth curve) with the fire growth coefficient of 0.178 kW/sec^2.

$$Q_{HGV}(t)=\begin{cases}\alpha t^2 & t<T_1\\ Q_{\max} & T_1\le t\end{cases}$$

The flammable liquid cargo (FLC) fire is assumed to have a linear hydrocarbon pool fire growth curve of 20 MW/minute as developed within the UPTUN program for European tunnel design criteria. The heat release rate up to 200MW is limited by the available drainage system which reduces the surface area of the flammable liquid pool size.

$$Q_{FLC}(t)=\begin{cases}\beta t & t<T_2\\ Q_{\max} & T_2\le t\end{cases}$$

The purpose of the 3% AFFF foam sprinkler system in I-90 tunnels is to stop fire from growing, including the FLC fire. The maximum fire size generated in the tunnel is limited by the fuel and the release time of the foam-sprinkler system. When the foam-sprinkler system reaches full flow, the fire should stop growing and either remain constant or be reduced. Validation of this statement depends on the fire size reached at the moment of the foam-sprinkler system activation. Early activation (small fire) will stop fire growth and will likely extinguish the fire. Late activation (large fire) may not stop fire growth as was demonstrated by previous studies [3].

Early detection of a small size fire will allow the fire sprinkler system to be activated before the fire size increases to unmanageable level. Figure 1 and 2 illustrate the controlled fire growth rates of flammable liquid and heavy goods fires with activation of the fire protection system. For a flammable liquid fire, detection at or before it reaches 5MW will allow the sprinkler system to be activated within approximately 1 minute after the fire detection. Once the sprinkler system is activated, the fire size is expected to be controlled at 35 - 40MW. For a heavy goods cargo fire, the detection of 5MW will allow the sprinkler system to be activated within approximately 1-3 minutes after the fire detection. Once the sprinkler system is activated, the fire size is expected to be controlled before it reaches 20MW. This approach allows for designing the Fire Life Safety systems, including tunnel ventilation, for a reduced fire size, such as 40 MW.

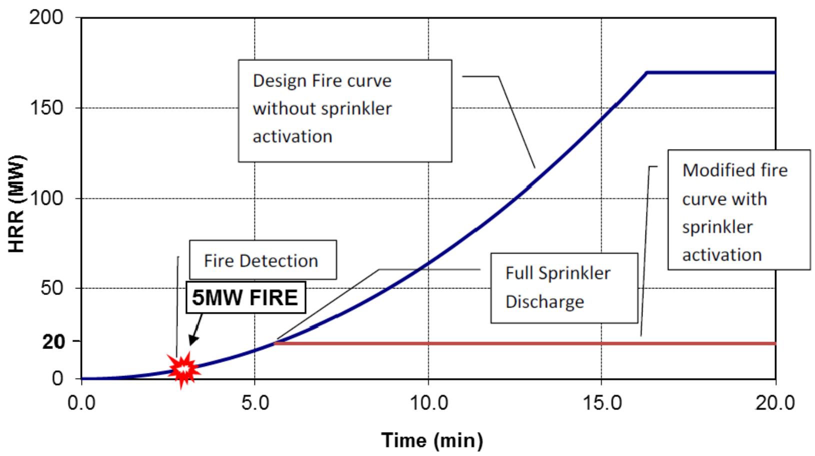

Figure 1 Heavy Goods Vehicle Fire Development Curve and its interaction with the sprinkler system

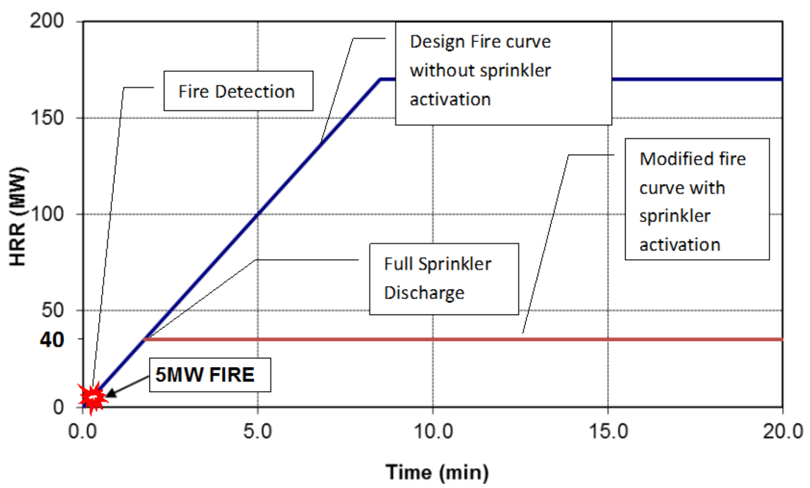

Figure 2 Flammable Liquid Cargo Fire Development Curve and its interaction with the sprinkler system

FIRE DETECTION

The fire detection system primary objective is early fire detection with minimum nuisance alarms during normal operation. Full scale pan fire tests were performed in the Eastbound Mount Baker Tunnel to determine the minimum fire size detectable by the enhanced fire detection technology with various fire sizes at various distances and elevations of obstructed and unobstructed fires. The goal was to assure detection of fires as small as 5 MW in one and a half minutes or less. The test collected performance data for both new and existing fire detection technology, including existing spot heat detectors, video flame and smoke detectors, infra-red and linear heat detectors. Tests with new fire detection systems demonstrated that open flame fires were detected within 60 seconds regardless of their elevation and distance from the fire detection cameras. Most of the open Flammable Liquid cargo fires could be detected within 30 seconds. Shielded fires are more difficult to detect, however their successful detection was also demonstrated by the fire detection cameras. Flammable liquid cargo fires were detected faster than HGV fires, due to their more rapid development.

Based on the full scale fire tests the following decisions were made for the expected fire size and fire curves at the I-90 tunnels for the Flammable Liquid fires:

1. Fire can be detected at an average of 33 seconds from a 0.5 MW fire, or at a value of 11.5 MW (based on the 20 MW/min fire growth)

2. Once the fire is detected it takes 60 seconds to react, confirm and activate the fixed fire suppression system. At 94.5 seconds the fixed fire suppression system can be activated (this includes 1.5 seconds for fire to reach 0.5 MW). At this time FLC fire can reach the size of 31.5 MW.

3. Once the sprinkler system is activated, it takes 15 seconds for water to fill the piping from proportioners to sprinkler heads at I-90 tunnels and another 15 seconds for a full sprinkler system discharge. At this time of 124.5 seconds from ignition the fire size reaches 41.5 MW

Figure 3 represents a fire curve for Flammable Liquid Vehicle Cargo fire based on an average fire detection time of 33 seconds. Considering a sufficient amount of water and 3% AFFF foam to control the fire at 41.5 MW, the tunnel ventilation system shall assure tenability at that fire size.

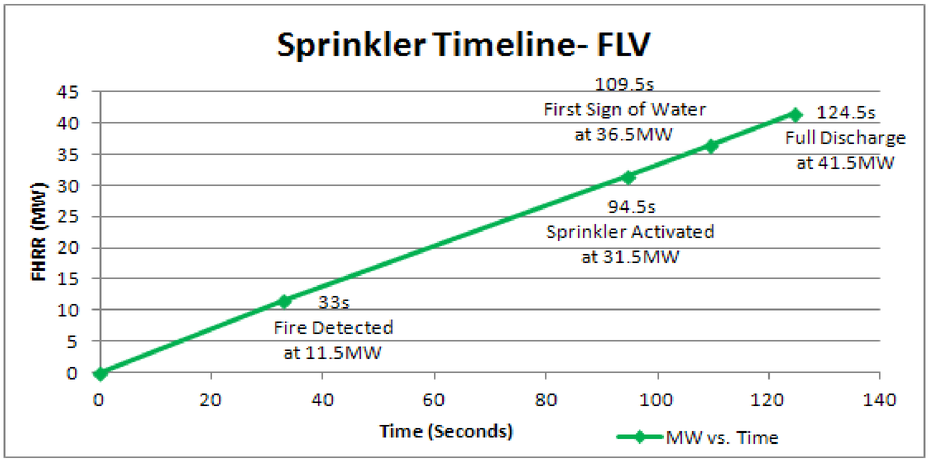

Figure 3 Flammable Liquid Vehicle Cargo fire curve with fire detection, fixed fire suppression system activation to control fire

Based on the full scale fire tests the following decisions were made for the expected fire size and fire curves at the I-90 tunnels for the Heavy Goods Vehicle fires:

1. Fire will be detected at 83 seconds from ignition (the maximum fire detection time), or at a value of 1.23 MW (based on the ultrafast power-law t squared fire growth curve with the fire growth coefficient of 0.178 kW/sec^2)

2. Once the fire is detected it takes 60 seconds to react, confirm and activate the fixed fire suppression system. At 143 seconds the fixed fire suppression system can be activated. At this time HGV fire can reach the size of 3.64 MW.

3. Once the sprinkler system is activated, it takes 15 seconds for water to fill the piping from proportioners to sprinkler heads at I-90 tunnels and another 15 seconds for a full sprinkler system discharge. At this time of 173 seconds from ignition the fire size reaches 5.33 MW.

Figure 4 represents a fire curve for Heavy Goods Vehicle fire based on a maximum fire detection time of 83 seconds. The curve shows that once the fire is detected as tested and timely activated, it can be stopped before it reaches 6 MW. However the project team decided to consider that due to possible longer confirmation of HGV fire and reaction time, the ventilation system shall be designed to 20 MW HGV fire.

The tests demonstrated that the advanced fire detection system and suitable fixed fire suppression system can detect fires early enough and control Flammable Liquid Cargo and Heavy Goods Vehicle fires at a manageable level. The tunnel ventilation system could be designed for environmental control using modified fire curves.

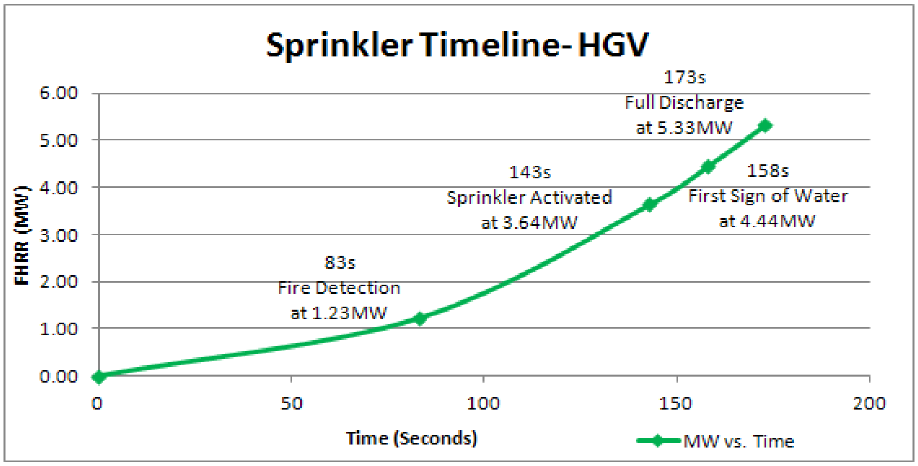

Figure 4 Heavy Goods Vehicle Cargo fire curve with fire detection, fixed fire suppression system activation to control fire

TUNNEL VENTILATION SYSTEMS MODIFICATIONS

The I-90 tunnels employ a fully transverse ventilation scheme designed with outdated ASHRAE ventilation requirements in place at the time of construction more than twenty five years ago. Analysis has indicated that the system may not be able to maintain tenable conditions ensuing from a fire involving heavy goods or flammable liquids cargo vehicles to which the tunnel is open. Different design strategies were implemented for Mount Baker and Mercer Island tunnels due to the prevailing traffic patterns and tunnel physical features. The design team performed full scale ventilation system tests at the Westbound Mount Baker Tunnel; full scale fixed fire suppression system tests with 3% AFFF at Eastbound Mount Baker Tunnel; Saccardo nozzle scale modeling tests for Mercer Island Tunnels; and CFD analysis to upgrade the existing smoke management systems with minimum construction impact on tunnel operation. CFD analysis numerically investigated the ventilation system alternatives at different fire locations and the effects of a water spray fire suppression system on convective flows while working in conjunction with a variety of ventilation systems to control a hyper-fast growth, 40 MW (FLV) fire by drawing conclusions from transient CFD analysis results for the Mt. Baker Ridge Tunnel and the Mercer Island Tunnel.

Westbound Mount Baker Tunnel

In the westbound tunnel, where tunnel traffic may be heavily impacted by adjacent highways traffic and city stadium events, tunnel traffic may be trapped on both sides of the fire. Such traffic condition requires smoke to be extracted as close to the fire as possible when tenability and safe egress are required on both sides of the fire. This challenges the retrofit of the old transverse ventilation system and requires the existing exhaust duct be divided into several sections, each approximately 1,000-ft long, to provide several exhaust ventilation zones in the lid section. Also additional means of evacuation through the existing supply air duct will be provided. The existing supply and exhaust fans will be upgraded to provide higher pressure by keeping the existing fan housings and replacing fan motors and impellers.

Figure 5 shows the concept of the ventilation modification in both eastbound and westbound tunnels with emphasis placed on the divided exhaust duct, sectionalization dampers, and fans upgrades. A new egress corridor was designed inside the existing supply duct in the west half of the tunnel.

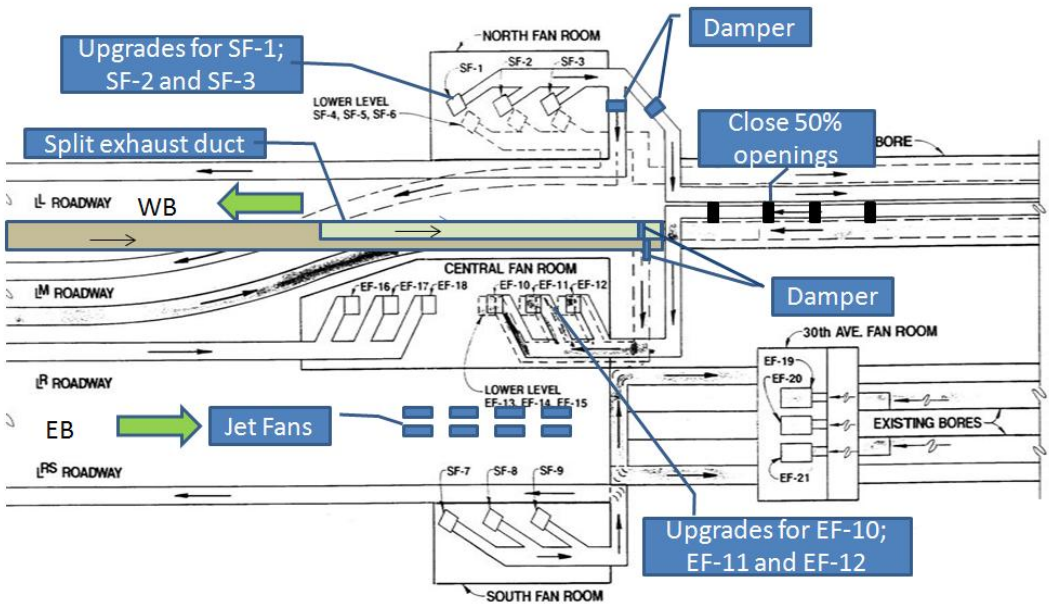

Figure 5 Mount Baker Tunnel Ventilation Modifications Schematic Diagram

Eastbound Mount Baker Tunnel

In the eastbound tunnel, where traffic "ahead" of the fire incident would be expected to be able to leave the tunnel successfully, a longitudinal ventilation system was designed to operate up to 16 new jet fans in the center section of the tunnel as shown in Figure 5 along with the existing transverse ventilation system using modified modes of operation. Two jet fans are installed at each location with one jet fan above the other. No other changes to the existing ventilation system are required. Results of the CFD analysis presented in Figure 6 shows entrance portal airflows as a function of time without and with sprinklers. Evaporative cooling of the smoke layer due to sprinklers reduced the buoyancy of the smoke layer as well as decreasing major friction losses downstream of the event owing to relatively higher air densities. The design team performed full scale fixed fire suppression system tests with 3% AFFF to determine its impact on smoke stratification and on the ventilation system performance and to verify the design approach.

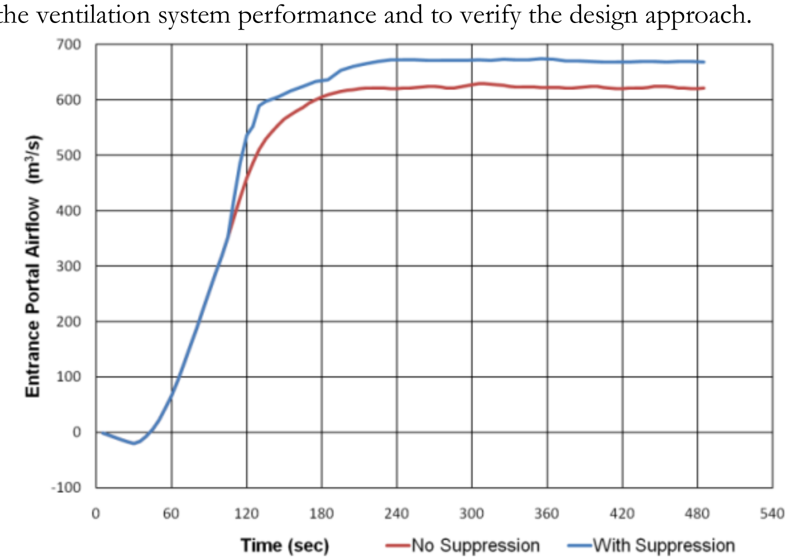

Figure 6 Entrance portal airflows with and without sprinklers.

Mercer Island Tunnels (MIT)

In the MIT traffic "ahead" of the fire incident would be expected to be able to leave the tunnel successfully. Therefore to mitigate fire risks, a longitudinal ventilation scheme has been designed where existing tunnel ventilation equipment will be retrofitted and reconfigured to deliver all supply air near the entrance portals through high velocity Saccardo nozzles and have all exhaust drawn near the exit portals (Figure 7). Computational fluid dynamics (CFD) modeling has been carried out to evaluate the performance of the proposed longitudinal ventilation system. The analysis has considered fires at multiple locations along both the eastbound and westbound roadways to assure that the range of challenges posed by the tunnel geometric characteristics – specifically the grade, cross-slope, and curvature – are sufficiently taken into account. Parametric studies were undertaken to: (1) identify the minimum required nozzle airflows to induce sufficient airflows for critical velocity and (2) quantify the effects of the operation of the sprinkler deluge system, such as the drag resulting from interaction of the water droplets and the longitudinal airflow. Additional two-dimensional CFD studies were undertaken to develop and optimize the shape and pressure drop characteristic of a unique nozzle fitting for each roadway that simultaneously turns and accelerates the airflow to the required nozzle discharge velocity. Scale modeling tests were performed in the lab to verify pressure losses through the "teardrop" Saccardo nozzle obtained from numerical calculations and CFD analysis. Modifications to the existing Mercer Island Tunnel transverse ventilation system are designed wherein longitudinal ventilation is achieved whereby ambient air is directed towards and delivered into the tunnel near the entrance portals at air velocity of 30 m/s through a Saccardo nozzle. The ambient air is injected at a shallow angle (20º) in the direction of traffic in order to induce air flow from the portal and amplify the longitudinal flow. Average velocities in the tunnel are expected to be critical or above critical thus preventing back-layering of smoke to tunnel occupants upstream of the fire. Additionally, all exhaust capacity will be drawn from near the tunnel exit portals.

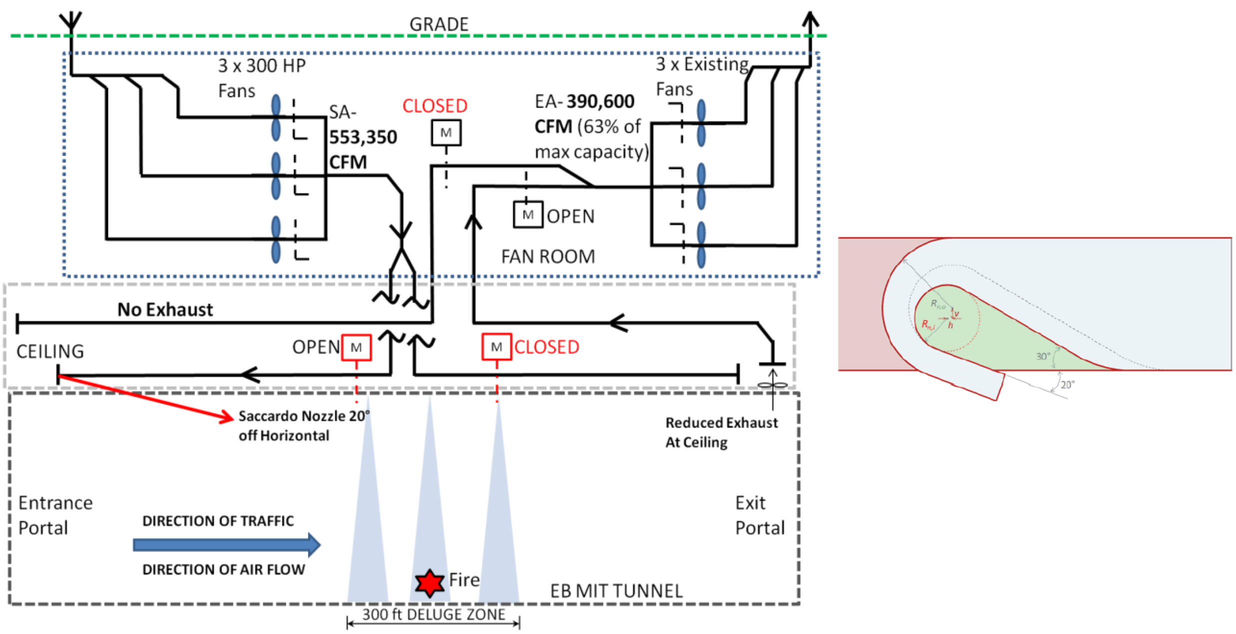

Figure 7 Schematic of the modified Mercer Island Tunnel ventilation scheme and "teardrop" Saccardo Nozzle

Inertial and viscous drag of water droplets impact momentum exchange between high velocity jet and entrance portal entrained airflows in a longitudinal ventilation system. In addition to momentum exchange, implementation of a longitudinal ventilation system also raises concerns about the potential effects on the performance and efficiency of the deluge system. The principal concern is that strong longitudinal airflows can blow water droplets particularly small ones, and foam from the area of the fire. It was concluded that evaporative cooling of the smoke layer due to sprinklers reduced the buoyancy of the smoke layer as well as decreasing major friction losses downstream of the event owing to relatively higher air densities. The existing supply fans will be upgraded to provide higher pressure by keeping the existing fan housings and replacing fan motors and impellers.

CONCLUSION

The I-90 fire life safety ventilation system was effectively upgraded to the latest requirements by:

- Upgrading the fire detection system;
- Sectionalization of the full transverse ventilation in the westbound WBRT to localize the exhaust capacity at respective potential fire locations;
- Conversion of the existing full transverse ventilation in the eastbound MBRT to longitudinal ventilation concept by installing new jet fans and revising the modes of operation of the existing system;
- Conversion of the existing full transverse ventilation in the Mercer Island tunnels to longitudinal ventilation concept by delivering all supply air into the tunnel near the entrance portals at high air velocity through the new Saccardo nozzles with all exhaust drawn near the exit portals.

Those modifications were achieved without major system modification, but upgrading fan motors, replacing fan shafts and impellers and installing additional motorized dampers and jet fans, to minimize the impact of construction. CFD analysis was performed for critical fire locations to confirm and optimize the design and modes of the emergency ventilation operation.

ACKNOWLEDGMENTS

The authors would also like to acknowledge the support of the project from Washington State Department of Transportation and Sound Transit.

NOMENCLATURE

α = 178 W/s^2 – HGV fire growth rate coefficient

β = 20 MW/min – FLC fire growth rate coefficient

T_1 = time at which maximum fire HRR for HGV is reached

T_2 = time at which maximum fire HRR is reached for FLC

Q_{max} = maximum fire HRR

REFERENCES

1. I Maevski; B Josephson; R Klein, (Jacobs Engineering); D Haight, PE; Z Griffith, (WSDOT) Full-Scale fire testing for fire detection, fire suppression and ventilation of I-90 tunnels in Seattle. 15th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels. Barcelona, Spain 18-20 Sept 2013 (pp. 789 – 804)
2. NFPA 502. National Fire Prevention Association Standard for Road Tunnel Bridges and Other Limited Access Highways, 2011 Edition.
4. NCHRP Synthesis 415. Design Fires in Road Tunnels. US Transportation Research Board of the National Academies. Washington DC, 2011. Consultant I. Maevski. (www.TRB.org)
5. Y Li, J Fay (Jacobs Engineering); D Kandra, J Alston (ARUP) Numerical simulations of the interaction of water spray fire suppression and emergency ventilation systems in vehicular tunnels. 15th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels. Barcelona, Spain 18-20 Sept 2013 (pp. 729 – 746)
6. J Alston; D Kandra; R Potter (ARUP) Upgrade of an existing transverse ventilation system to a longitudinal system using Saccardo nozzle 15th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels. Barcelona, Spain 18-20 Sept 2013 (pp. 89-104)
7. ASHRAE. 2011. ASHRAE Handbook-HVAC Applications. Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.