Wind impact on fire emergency ventilation for a road tunnel with water-based fire protection systems

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ABSTRACT

Non-mechanical ventilation systems for short tunnel configurations may provide design solutions by utilizing generous ceiling volume to store and vent developing smoke plumes. However, climactic conditions of prevailing wind intensity and direction can greatly impact effectiveness of non-mechanical ventilation systems. This paper will address how to review the wind rose data and extract the wind flow parameters for the analysis, as an attempt to provide a standard guideline on how the wind data should be interpreted for fire smoke hazards analysis, and to evaluate the smoke tenability in a vehicle fire.

Based on an example 200 m long tunnel formed by a land bridge, this paper will discuss that mechanical ventilation is necessary for achieving the desired ventilation effect under adverse wind condition while considering a water-based fire protection system in operation. Engineering analysis developed with computational fluid dynamics (CFD) provided a detailed investigation as to what wind developed air circulation patterns and pressures are counter-productive in the configuration. Consequently, mechanical ventilation with jet fans must be considered based on the tunnel geometry. This will help maximize the available tenable time for the worst-case fire incident scenario.

Keywords: tunnel fire safety, roadway lid structure, wind rose, tunnel portal configuration, mechanical ventilation.

1 INTRODUCTION

The development of underlid roadway in metropolitan areas such as in Seattle, Washington brings substantial benefits to the urban development by increasing the land use efficiency. The addition of a lid on top of an existing roadway creates enclosed space under the lid that warrants comprehensive fire safety analysis and ventilation design study. The 2020 version of NFPA 502 chapter 7.2 describes the minimum fire protection and fire-life safety requirements based on the tunnel length and traffic volume.

The width of subject bridge is approximately 200 m on the eastbound lane underpass. Based on NFPA 502, engineering analysis is required for its fire protection system. Because the subject roadway traffic and the bridge width qualify the underpass as a Category A road tunnel in terms of the minimum fire protection and fire-life safety requirements, mechanical ventilation is not a mandatory requirement for handling the fire and smoke to ensure a tenable environment in case of a fire emergency. However, the local wind condition needs to be considered when analyzing the fire smoke tenability.

Considering the predicted future traffic density of 2200 vehicle/lane/hr and the fact that there is no restriction of heavy goods vehicles and flammable liquids cargos, a water-based fire protection system using foams has been selected. This analysis will focus on the impact of fire protection systems operation and the effects of local wind conditions.

2 LOCAL WIND

Fire hazard development in the road tunnel is affected by atmospheric wind conditions. Wind flowing into the portal limits the natural ventilation flow capacity out of the enclosed space and ventilated smoke towards the egress direction. By flowing into an enclosed space, wind could also push a stratified, hot smoke layer down into the occupied zone of the enclosed space, infringing on occupant health and hindering egress.

Implementing wind boundary conditions for fire hazard modeling using CFD requires analysis of applicable, predominant wind conditions at the location of the enclosed space. Analysis was performed to determine which wind condition had the most adverse impact on the tenability condition inside the modeled enclosed space. Currently, there are no consistent standards on how to extract the wind velocity for analyzing the tunnel ventilation based on historical observations. In this project, wind rose plots from Seattle-Tacoma International Airport were analyzed as the reference to establish maximum wind speed and direction throughout the year for the model. Because the airport is proximate to the subject bridge, wind rose plots from the airport provide sufficient, relevant data for the predominant wind speed and flow direction relative to the portals. Additionally, given the elevation and exposure of the project site; the subject road tunnel is susceptible to direct easterly and westerly winds. This exposure impacted the decision to use the SeaTac Airport wind rose for its given elevation and proximity to the project site as a representative of the most adverse design case.

Adverse wind impacts are represented within the CFD simulations as an airflow speed value parallel with the tunnel roadway. The most adverse wind has been identified based on wind rose in the month of June for the westbound lane and in the month of December for the eastbound lane, as shown by Figure 2-1. June was determined as the month when adverse wind conditions to the tunnel's westbound traffic occur. June wind rose plot indicates the highest probability of westerly wind throughout the year that blows straight into the enclosed underlid roadway space, which presents adverse wind condition to the first fire scenario – westbound lane simulation with fire location near west portal scenario. Meanwhile, December was determined as the month when adverse wind conditions to roadway lid's eastbound traffic occur. The December wind rose plot indicates the highest probability of easterly wind throughout the year that blows straight into the enclosed underlid roadway space, which presents adverse wind conditions to the fire scenario – eastbound lane simulation with fire location near east portal scenario.

Wind profiles were applied to all CFD simulations based on the top 5 percentile maximum wind speed indicated by the wind rose plots and applicable portal coefficient factors depending on the angle of maximum wind with respect to the underlid roadway exit portals. Figure 2-2 provides an overlaid wind rose plot illustration to the underlid roadway west portal plan and fire location near west portal. Meanwhile, Figure 2-3 provides an overlaid wind rose plot illustration to the underlid roadway east portal plan and fire location near east portal.

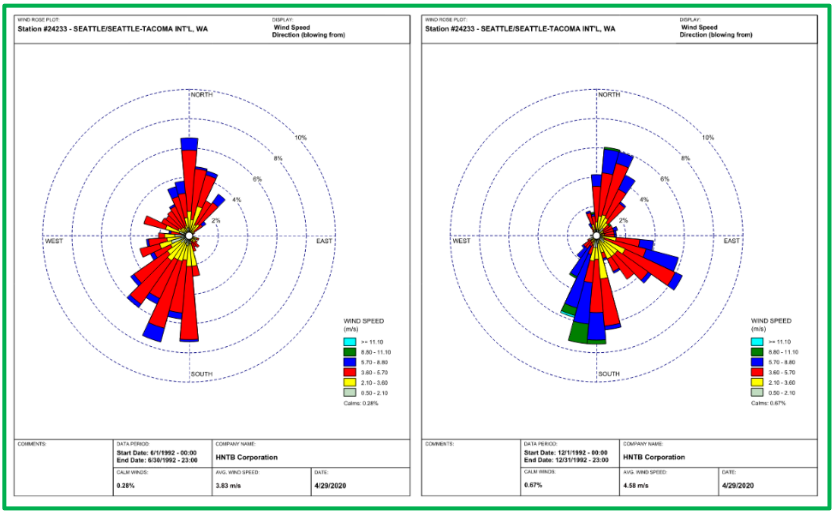

Figure 2-1. February (Left) and December (Right) Wind Rose Plots at Seattle-Tacoma International Airport

To provide realistic wind velocity conditions around the underlid roadway domain, atmospheric wind velocity profile was applied to the CFD simulations. The atmospheric wind profile provides power law profile that represents increasing wind velocity as elevation increases. As shown by the wind rose plots on Figure 2-2 and Figure 2-3, maximum adverse wind speed from west and east directions at underlid roadway location was determined to be 8.8 m/s. This maximum adverse wind speed was set at reference elevation of 3 meters, a typical wind anemometer height used to generate wind rose plots.

According to Blendermann[1], wind tunnel tests performed on various portals of road tunnels demonstrated wind pressure differences along the tunnel. The research performed by Blendermann provides applicable portal coefficient factors for a tunnel structure based on geometry of the tunnel portal and the wind angle of attack with respect to tunnel portal. According to the tunnel geometry categorization presented in the research, portals of the subject underlid roadway fall under the ‘below ground level with vertical sidewalls’ category. Based on the applicable wind rose plots and subject underlid roadway plan, the adverse wind scenario from the month of June flows to the underlid roadway west portal at 11° angle while the adverse wind scenario from the month of December flows to the underlid roadway east portal at 11° angle. Based on these angles as well as subject underlid roadway portal geometry, a portal coefficient factor of 0.55 was determined and applied to maximum adverse wind speed at the subject underlid roadway location.

The applied portal coefficient factor reduces the maximum adverse wind speed that could occur to the underlid roadway space to 4.8 m/s from either the west or east direction. To provide realistic wind velocity condition around the subject underlid roadway domain, atmospheric wind profile of 4.8 m/s was applied at the portal; westerly wind profile for the first fire scenario (westbound lane simulation with fire location near west portal scenario) and easterly wind profile for the second fire scenario (eastbound lane simulation with fire location near east portal scenario). Wind profile was applied right from the start of CFD simulation to represent condition where wind flow was established at the time of fire incident occurred and fire initiation started.

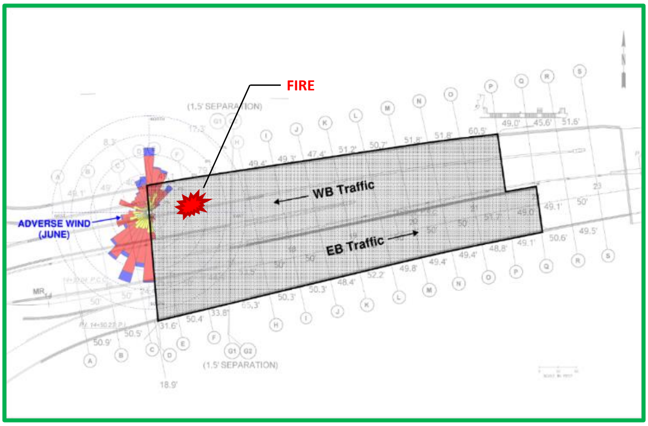

Figure 2-2. Adverse Wind Conditions for Westbound Lane Simulation with Fire Location Near West Portal Scenario

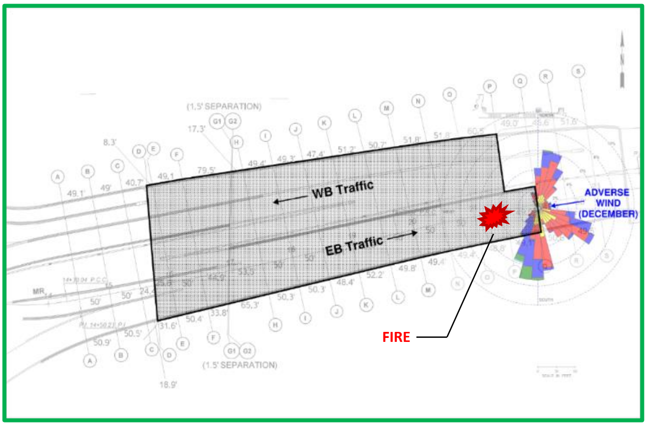

Figure 2-3. Adverse Wind Conditions for Eastbound Lane Simulation with Fire Location Near East Portal Scenario

3 HRR WITH FFFS

Fire Heat Release Rate (HRR) will be much lower when Fixed Fire Fighting System (FFFS) are applied, FFFS effects are considered in the CFD analysis of fire smoke tenability. Seattle Fire Code Amendments to 2011 edition of NFPA 502 state that water-based fire-fighting systems are required in road tunnels as part of an integrated approach to the management of fire and life safety. For Flammable Liquid Cargo (FLC) fire hazards, protection shall be based on engineering analysis and approved by the authority having jurisdiction (AHJ).

It is presumed FFFS is required to protect major structural elements, aid first responders, and slow, stop, or reverse the rate of fire growth – acting as a 'fire control system'. Based on the perceived most adverse case of fire hazards; and for the sake of this analysis - it is not assumed the FFFS will act as a 'fire suppression system' which can reduce the energy output of a fire upon system activation. However, water-only FFFS is presumed to control a heavy goods vehicle (HGV) fire growth, and an aqueous film forming foam additive (AFFF) to the FFFS system is presumed to control a flammable liquid cargo (FLC) fire event; the latter is presumed based on industry specific studies and full-scale testing available nowadays.

The FFFS will use a deluge valve system as part of the integrated fire life safety system for the subject roadway, including open head nozzles and a dry pipe system. Operational characteristics of the FFFS are assumed as follows:

- The FFFS shall be installed, inspected, and maintained in accordance with NFPA 13.
- Until water supply is verified; assume a deluge sprinkler zone is 10,000 ft^2 with dimensions that vary depending on lane and structural limitations.
- System will have the ability to supply two contiguous fire zones simultaneously.
- Water demand for the deluge sprinklers is presumed to be 0.16 GPM/ft^2.

The water supply for the system shall be capable of supplying the system demand for a minimum of 1 hour based on NFPA 502. The water supply system must also be adequate to supply the required working pressure.

Sprinkler heads of sprinkler zone are modeled within FDS using a software integrated device which represents the features of a deluge sprinkler system. The fire Heat release Rate (HRR) growth curves are the input for the CFD model and its interaction with the sprinkler system are represented with its HRR capped assumed remain constant till the end of the simulation, as shown in Figure 3-2 and Figure 3-3. This analysis will study the impacts of the fire suppression sprinkler system on smoke tenability of the underlid roadway. The following characteristics will be used in the analysis to observe the interaction of a deluge sprinkler system and fire smoke hazards:

- Sprinkler spaced on a 10’ x 10’ grid within the underlid roadway.
- Two sprinkler zones modeled and activated above the fire location (20,000 ft^2 total area).
- 0.16 GPM/ft^2 (6.5mm/minute) sprinkler head demand. Simulated sprinkler heads modeled at 16 GPM/head (60.567 L/min).
- 300 µm sprinkler water particle diameter.
- 3,200 GPM or 192,000 gallons per hour total sprinkler heads discharge volume for two zones activation with 1,600 GPM per zone.

It is assumed fire events are detected via linear heat detectors within the underlid roadway located centered over traffic lanes. The deluge sprinkler zone(s) are discharged where a fire is detected. If a fire is detected across two adjacent zones, then the two congruent zones will be activated. Though the FFFS system can be activated manually, it is assumed the activation of the FFFS sprinklers systems (with or without foam additives) are activated via linear heat detectors. This is calculated to occur at 16 seconds and 96 seconds for fire scenarios of FLC and HGV, respectively.

Studies have shown that timely activation of a fixed fire suppression system (FFSS), with or without foam, can control a fire event and suppress its growth [2,4]. The extent of the fire event’s suppressed growth and decay depend on the fire type, environmental factors, ventilation systems in place, detection time, and FFSS operation and configuration. Although contested in some industry studies, it was assumed for this analysis that the only form of successful FFSS for an FLC fire event is with an aqueous film-forming foam (AFFF) solution additive. It was also assumed that an FFSS with a Class B 3% AFFF solution activated via a deluge valve system within the underlid roadway and that, upon activation, it capped the fire growth at a peak heat release rate of 60 MW. For this observation it was assumed that FFSS activation time is considered appropriate per allotted time for fire detection and positive alarm sequence operation.

There may be other cases/studies showing that a foam FFSS system will completely extinguish or significantly reduce a fire size to no more than 10% of its peak heat release rate. However, this analysis maintained the peak heat release rate to preserve a conservative approach for ventilation operation observations within the CFD model. It was assumed that the high-velocity longitudinal ventilation applied to the subject underlid roadway would not have a diminishing effect on the FFSS's ability to suppress the fire event [3].

The resulting fire growth curves which will be used in analysis simulations are summarized in the following Table 1, and graphically in Figure 3-1 and Figure 3-2.

Table 1. Fire Event Peak HRR and Growth

Fire Scenario Event	Peak HRR (MW)	Simulated Peak HRR after FFFS Activation (MW)	HRR Growth Rate
FLC	300	56	20 MW/min
HGV	150	60	t^2, fast

Combination of full-scale fire tests and CFD simulations demonstrating pyrolysis of the fuel materials yield the following fire characteristics which were used in all the simulations with the FLC and HGV fire events.

- Steady-state fire growth curve.
- Heat of Combustion of 50 MJ/kg.
- Carbon Monoxide (CO) yield of 0.0532.
- Soot yield of 0.15.

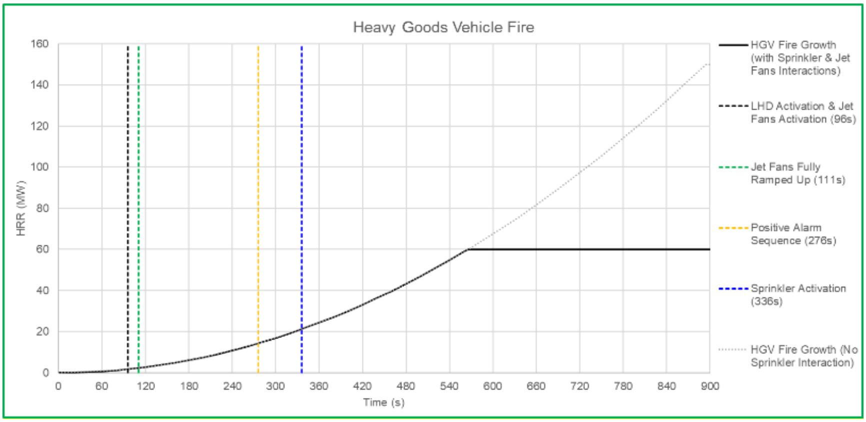

Figure 3-1. HGV Fire Growth Curve with FFFS Sprinkler Activation

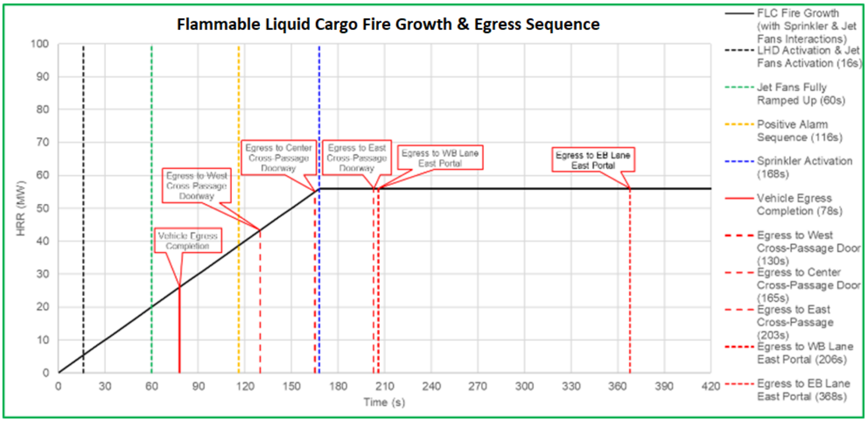

Figure 3-2. FLC Fire Growth Rate with Foam Sprinkler Activation and Tunnel Egress Sequence

4 CFD ANALYSIS

Visibility contour slices generated from CFD simulations were compared with the relevant criteria from NFPA 502. Multiple smoke mitigation features were analyzed for both fire location near west portal and fire location near east portal to determine whether those features would comply with the relevant governing criteria.

As shown in the figures 4-1, 4-2, 4-3 and 4-4, CFD simulation results are presented in the form of colored contours taken at sections in elevation, as well as in plan views; they are referred to as visibility contours. For this analysis, the colors illustrate levels of visibility as affected by smoke from the fire event. The color scheme ranges from blue, indicating objects are discernible to an underlid roadway occupant at a distance of 10 meters, to red, indicating an occupant cannot discern an object directly in front.

In the CFD simulations, visibility contour images in elevation view are generated by taking a longitudinal plane near the centerline of flammable liquid spill. Visibility contour images in plan-view are generated by taking a plane slice at 2.5 meters above roadway surface. Per NFPA 502, 2.5 meters indicates the height of the egress pathway for underlid roadway occupants.

Initial benchmark simulations were performed using the baseline model where none of the smoke mitigation features were added and applied. These benchmark simulations were based on the subject underlid roadway design and performed on both westbound lane and eastbound lane portions of the lid. Flammable liquid spill fire scenario was selected as the most adverse and the most conservative fire incident scenario that could occur underlid roadway. Adverse wind conditions were applied to flow from the west on the westbound lane fire location near west portal simulation and from the east on the eastbound lane fire location near east portal simulation.

Figure 4-1 and Figure 4-2 provide plan and elevation views of visibility contour slice taken from the westbound (WB) lane with west portal fire location scenario simulation at the vehicle egress completion time, which is 78 seconds. Meanwhile, Figure 4-3 and Figure 4-4 provide similar views of visibility contour slice taken from the eastbound (EB) lane with east portal fire location scenario also at the vehicle egress completion time.

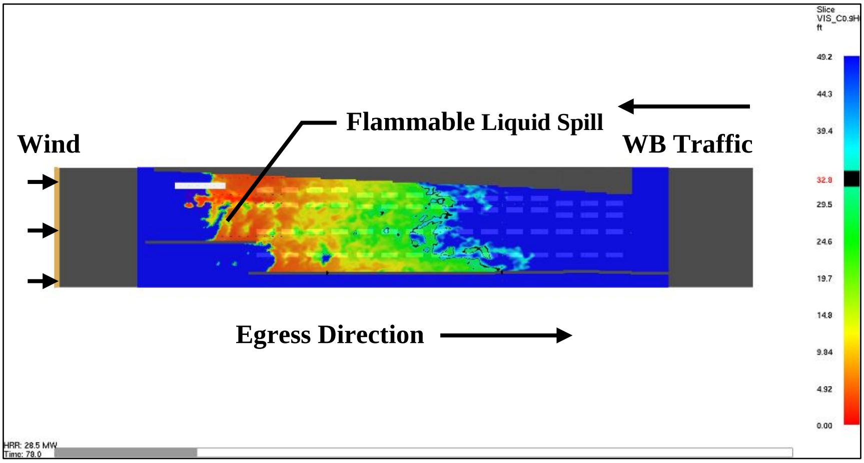

Figure 4-1. Benchmark Westbound Lane Simulation with West Portal Fire Location Scenario – Plan View of Visibility Slice at Vehicle Egress Completion Time

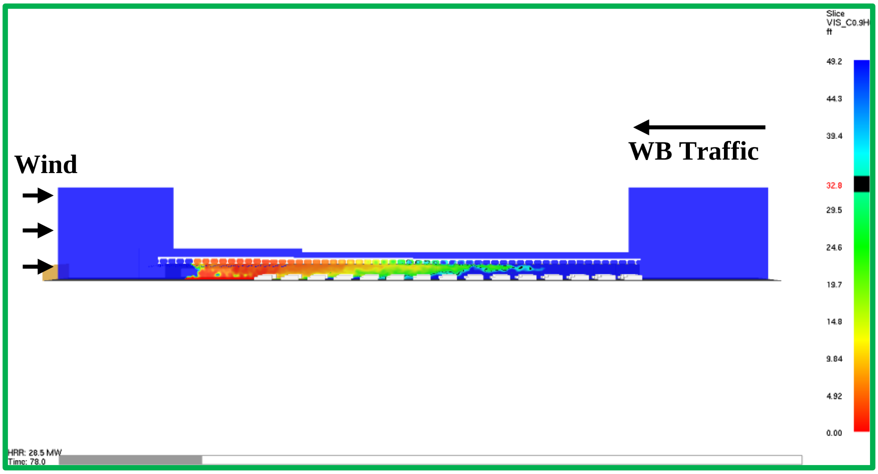

Figure 4-2. Benchmark Westbound Lane Simulation with West Portal Fire Location Scenario – Elevation View of Visibility Slice at Vehicle Egress Completion Time

The results of initial benchmark simulations indicated that tenable conditions under the lid could not be achieved without any means of smoke mitigation and fire life safety features implemented to the underlid roadway. As shown by Figure 4-1 to Figure 4-4, smoke conditions near fire incident locations have expanded considerably thus creating untenable conditions even at the time of vehicle egress completion. Without any smoke mitigation measures and fire life safety features, these conditions would have only gone worse over time.

This has shown that mechanical ventilation is required, as wind has blown the smoke towards the egress zone, and occupant will have to evacuate under smoky conditions if the system rely on natural ventilation and mechanical fans are not considered.

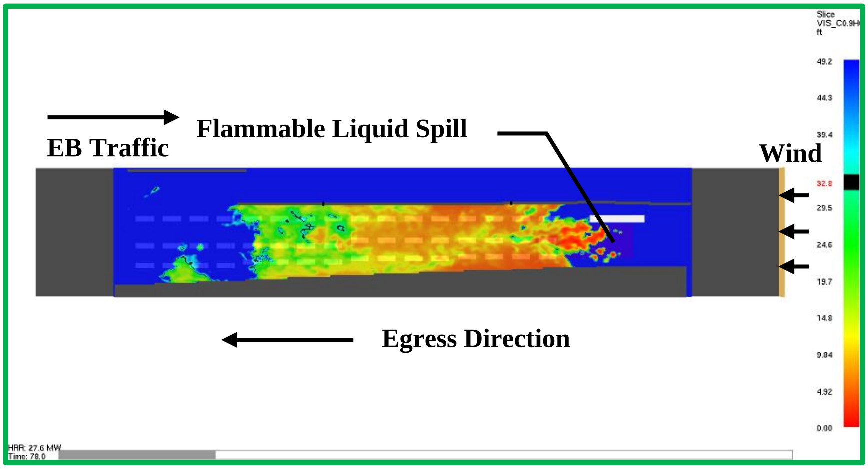

Figure 4-3. Benchmark Eastbound Lane Simulation with East Portal Fire Location Scenario – Plan View of Visibility Slice at Vehicle Egress Completion Time

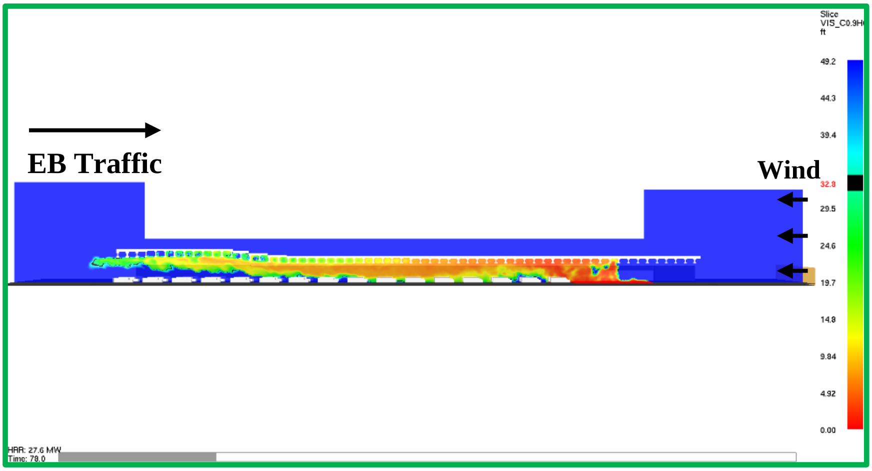

Figure 4-4. Benchmark Eastbound Simulation with East Portal Fire Location Scenario – Elevation View of Visibility Slice at Vehicle Egress Completion Time

5 CONCLUSIONS

For the subject tunnel that is only 200 meters long, it is classified as category A tunnel per clause 7.2 of NFPA 502 – 2020, and mechanical ventilation can be omitted. However, based on the local wind condition, CFD simulations performed in this fire life safety study conclude that mechanical ventilation is required on this 200 m long tunnel, which is under a land bridge.

The paper also introduced 5 percentile maximum wind speed criteria based on wind rose data, it should be a basis for discussion within the community to come up with a standard guideline on how the wind data should be interpreted, so that the wind velocity can be extracted for use in the CFD analysis.

CFD modeling also showed that smoke mitigation features such as wind baffles, and side wall openings applied to the tunnel portal could not provide adequate tenable conditions for egress during a fire incident inside this short tunnel, and mechanical ventilation is required. The system should also include AFFF solution additive to the tunnel fire suppression sprinkler system working together with linear heat detectors, standpipe system, egress cross-passages, and structural fire protection and spalling mitigation for the final proposed design solution.

This example showed that NFPA 502 performance-based criteria including traffic density provides guidance for emergency ventilation consideration. Mechanical ventilation was found to be necessary to mitigate inadequate safety conditions created by rapid fire hazard development interaction with probable local wind conditions. Any design should consider the specific situation and come up with a design on case-by-case basis.

6 REFERENCES

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