EMERGENCY OPERATING MODE ANALYSIS FOR THE TED WILLIAMS TUNNEL

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Abstract

The CFD model SOLVENT was used to refine the emergency ventilation operating mode matrix for the Ted Williams Tunnel. The tunnel is served by a full transverse ventilation system. The matrix identifies how each ventilation zone is to be operated as a function of fire incident location. SOLVENT was applied to simulate the interaction of the fire and the ventilation system. The analysis addressed the fire locations where the ventilation modes would change (or transition). For the two operating modes applicable to each mode transition point, the model determined the hazardous regions of the tunnel, and how these regions were affected by ventilation system operation and delivered capacity during the fire scenario. By comparing the results of the simulations and varying the locations of the transition points accordingly, the final locations for these points were determined and a new matrix was developed.

1.0 Introduction

The Ted Williams Tunnel (TWT), a major element of the Central Artery/Tunnel project in Boston, was opened for limited operation in December 1995. The tunnel is comprised of one eastbound and one westbound roadway, each designed primarily to serve unidirectional traffic. The sub-aqueous portion of this 2.53 km tunnel is an immersed tube design serving four lanes of traffic, two in each direction. The land sections are of cut-and-cover construction with varying tunnel cross-section and lanes of traffic. The tunnel is served by a full transverse ventilation system which includes 2 ventilation buildings, 7 ventilation zones, 14 duct systems, and 34 fans.

To facilitate the proper operation of the ventilation system during a fire emergency, an emergency operating mode matrix was developed. The modes are intended to minimize the extent of the hazardous effects of the fire (smoke and high temperature) on the traffic assumed stopped behind the incident. Traffic ahead of the incident is assumed to exit the tunnel.

The modes were initially selected to maximize longitudinal flow at the incident location, moving smoke and heat toward the empty end of the tunnel. At various points along the roadway, the ventilation system operating mode changes. The westbound section contains three such transition points and the eastbound section contains four. At these transition points both modes should provide about the same level of smoke/heat management capability. In the initial development of the matrix, factors that affect the extent of the hazardous region such as tunnel grade, specific extraction and supply rates per unit length of tunnel, tunnel and vehicle resistance to airflow, and fire heat release rate were not taken into account. Hence, the appropriate locations for the mode transition points could only be estimated.

To refine the matrix, SOLVENT [1], a CFD model customized for tunnel ventilation analysis, was utilized. SOLVENT is able to account for the factors identified above to determine the hazardous regions of the tunnel and how these regions are affected by ventilation system operation and delivered capacity during the fire scenario. By simulating fire incidents at the proposed mode transition points, the location of these points were finalized.

2.0 Ventilation System Description and Operation

The westbound section of the TWT extends from portal to portal. The eastbound section, upon reaching East Boston, splits into two distinct sections: one leading to Logan Airport and the other a continuation of Interstate I-90. A schematic of the tunnel is shown in Figure 1.

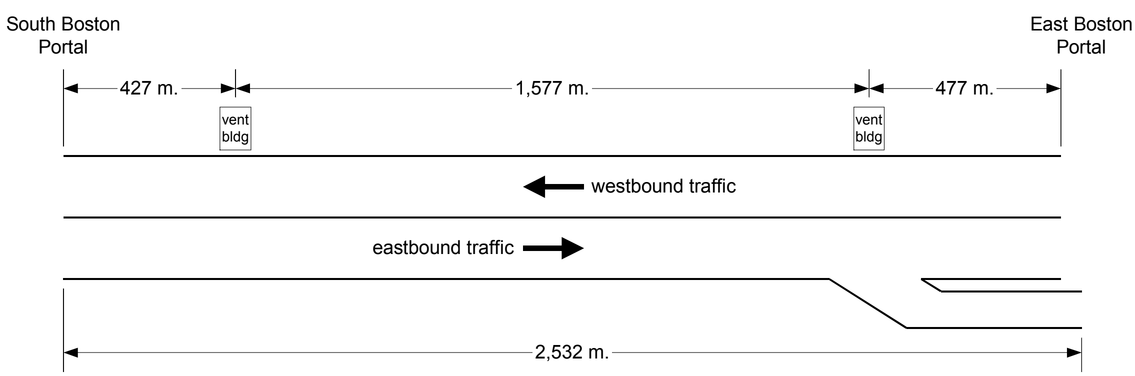

Figure 1. Schematic of Ted Williams Tunnel

A full transverse ventilation system is used to ventilate the tunnel. Each roadway is served by supply and exhaust ducts extending from the ventilation buildings. Air is supplied through flues near the roadway and extracted through ports in the ceiling. A portion of roadway served by common duct and fan group systems is referred to as a zone. The westbound and eastbound sections are comprised of three and four ventilation zones, respectively.

The ventilation system is designed for maximum delivery rates of 0.155 m^3/s per lane-meter (100 cfm per lane-foot) for exhaust and 0.101 m^3/s per lane-meter (65 cfm per lane-foot) for supply. The maximum delivery rate of each duct is achieved by operating all fans serving the duct at maximum design speed.

Lower delivery rates are achieved by reducing fan speed through adjustable frequency controllers and/or operating fewer fans.

Under normal conditions, the ventilation system is usually operated in a balanced mode, with the exhaust rate equal to the supply rate. The rate used is a function of the traffic condition in the tunnel. During a fire incident, the ventilation system is switched to emergency mode, with each zone being operated in either emergency exhaust or emergency supply depending on the fire location. Emergency exhaust mode corresponds to 100 percent exhaust capacity and 20 percent supply capacity. Emergency supply mode corresponds to 100 percent supply and no exhaust. The non-incident roadway is operated in emergency supply mode to facilitate evacuation through cross-passages.

3.0 Methodology

From the standpoint of ventilation, the eastbound and westbound tunnels are essentially independent of each other. Consequently, a separate CFD model was developed for each section.

To refine each transition point location, two steady-state simulations were performed with a 20 MW fire located at the estimated transition point. Each simulation addressed one of the emergency ventilation modes applicable to that transition point. If the results showed that motorists trapped behind the fire would not be afforded about the same level of protection in both modes, a new transition point location was chosen and the two simulations were repeated. This process continued until both modes provided basically the same level of safety behind the fire. Note that the ventilation mode transition points represent the locations in the tunnel where the level of safety provided is a minimum. Away from the transition point, the level of safety provided by the respective ventilation mode would increase.

For selected transition points, transient simulations were performed to evaluate the benefits of operating one ventilation mode versus the other during the early stages of the emergency. These results were used to support final recommendations for all transition point locations.

4.0 Analysis

In this section, the process of establishing the transition point located in zone WB2 (the middle zone in the westbound tunnel) is described. The other six transition points in the TWT—two more in the westbound tunnel and four in the eastbound tunnel—were similarly established.

The westbound tunnel geometry is shown in the following figure.

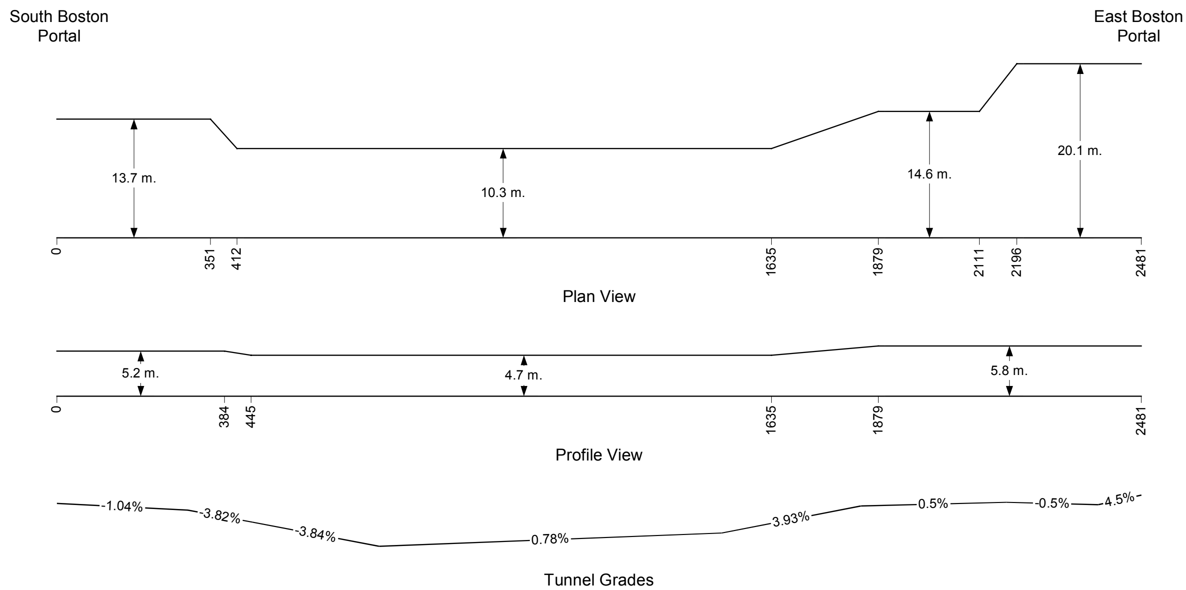

Figure 2. Westbound Tunnel Geometry

The initial mode transition point for zone WB2 was identified at 1,340 m from the South Boston portal. Two steady-state simulations were performed for a fire at this location. The heat release and smoke generation rates were 20 MW and 0.02 kg/sec, respectively. In the first simulation (E1), zones WB1 and WB2 were operated in emergency exhaust and WB3 was operated in emergency supply. The fan operation in the second simulation (S1) was similar, except that the incident zone, WB2, was operated in emergency supply. The scenario simulated is depicted below.

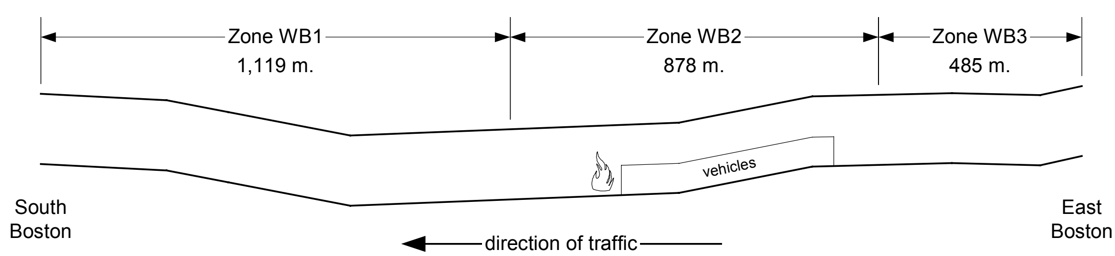

Figure 3. Fire Scenario at Estimated Transition Point

Two lanes of vehicular traffic extending 500 m were assumed to be trapped in the tunnel behind the incident. The number of vehicles in the tunnel was determined from peak hour traffic volume and an estimated response time of 2 minutes for the traffic control system to react to the incident and stop additional traffic from entering the tunnel. To represent the resistance to airflow due to the vehicles, resistance was applied to all cells in the tunnel cross-sections where the vehicles were located. The effective resistance factor per 100 m was 0.673 in the immersed tube section and 0.318 in the cut-and-cover section. The resistance factors were derived as a function of vehicle drag coefficients and tunnel blockage ratio.

The simulation results are shown in Figures 4 and 5. The longitudinal air velocity approaching the fire site in both cases is similar in magnitude. A positive value corresponds to airflow moving eastbound. The temperature contour comparisons indicate that east of the fire, both ventilation modes limit the hazardous region to within 60 m of the fire site. When the incident zone is operated in supply, the high temperatures in this region are a bit more stratified, but both modes apparently provide nearly the same level of protection to the trapped motorists.

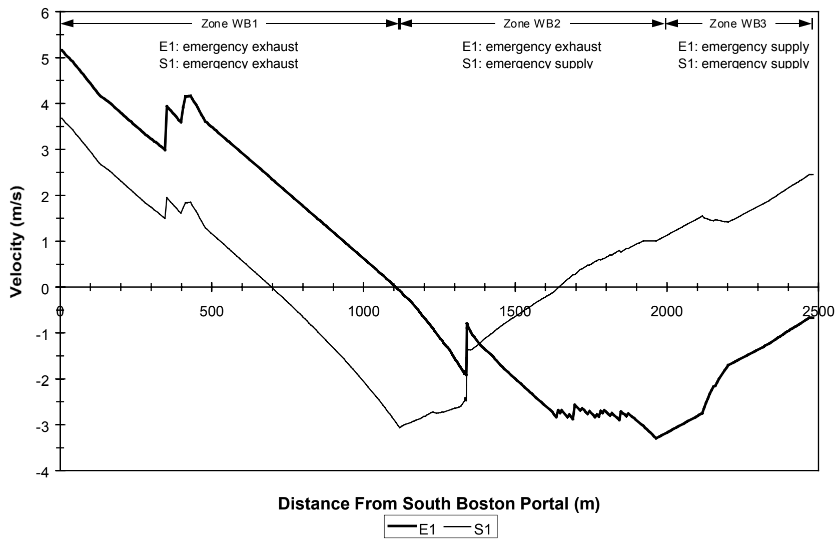

Figure 4. Bulk Velocity

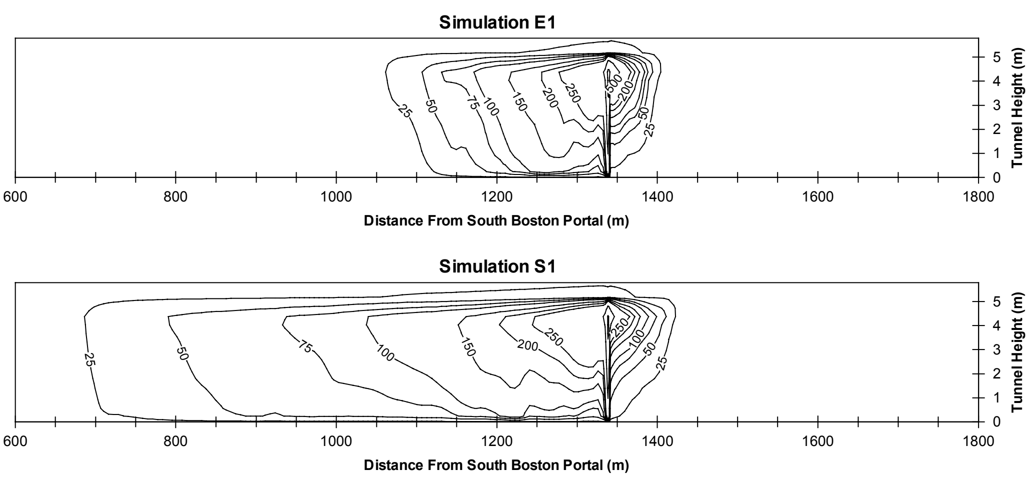

Figure 5. Temperature Distribution (°C)

Two transient simulations (TE1 and TS1) were performed for an incident at this location to compare the protection provided by the two ventilation modes when realistic delays in emergency response and fan run-up/run-down are included in the analysis. The fire begins at time equal to zero. The fire heat release and smoke generation rates increase linearly from 0 to 20 MW and 0.02 kg/s over a period of 3 minutes and remain constant thereafter.

At the start of the fire, the ventilation system is operated in balanced mode as it would under normal, peak hour traffic conditions (supply and exhaust ducts operating at 50 percent and 33 percent capacity, respectively). The sequence and delay times used to transition the ventilation system from a balanced mode to the emergency mode were based on discussions with tunnel operating personnel and tests performed at the tunnel. The fan system events and the fan system run-up/run-down times are listed in the following tables.

Key Fan System Events for Transient Simulations

Time (sec)	WB2 in Exhaust Mode	WB2 in Supply Mode
0	Balanced Supply and Exhaust	Balanced Supply and Exhaust
180	WB2: Emergency Exhaust Mode	WB2: Emergency Supply Mode
195	WB1: Emergency Exhaust Mode	WB1: Emergency Exhaust Mode
225	WB3: Emergency Supply Mode	WB3: Emergency Supply Mode

Fan System Run-Up/Run-Down Times

Exhaust Fan Systems		Supply Fan Systems	
Transition	Time (sec)	Transition	Time (sec)
33% to 100%	150	50% to 100%	90
33% to off	60	50% to 20%	60

Tunnel temperature and smoke distribution at various times are compared in Figures 6 and 7. The temperature contours are superimposed on the smoke distribution. The visible edge of the smoke front corresponds to regions where the smoke dilution levels lie between 100:1 and 500:1 of the maximum smoke concentration at the fire site. The inner and outer edges of the gray smoke region correspond to these dilution levels. Consequently, the smoke front lies within the gray region.

Just prior to activating the emergency ventilation mode in zone WB2, the elevated temperatures and smoke are stratified and extend approximately 213 m east and 183 m west of the fire. When the incident zone is operated in exhaust, the hazardous region continues to spread for an additional 30 seconds until it extends 244 m east of the fire. As the fans are brought online, longitudinal flow accelerates towards the fire from the east, forcing the high-temperature and smoke-filled region to recede. Steady-state conditions are reached by 400 seconds. When the incident zone is operated in supply, however, the high-temperature region continues to spread for 80 seconds after the emergency mode is activated, extending approximately 305 m east of the fire. The smoke continues to move east of the fire and the hazardous region does not recede significantly by 400 seconds.

Examination of the steady-state longitudinal air velocity graphic (Figure 4) provides an explanation for the different results seen when the two ventilation modes are evaluated on a transient basis. When zone WB2 is operated in supply, a zero flow point in the tunnel occurs approximately 305 m east of the fire. Therefore, as the flow in the tunnel transitions to its steady condition, the longitudinal flow at the extreme of the hazardous region fails to force the high temperatures and smoke back towards the fire. Additionally, the supply air tends to de-stratify the high temperatures and smoke due to mixing.

Alternatively, when the zone is operated in exhaust, the extraction inhibits the spread of the hazardous region while the longitudinal flow in the tunnel transitions to its steady-state distribution.

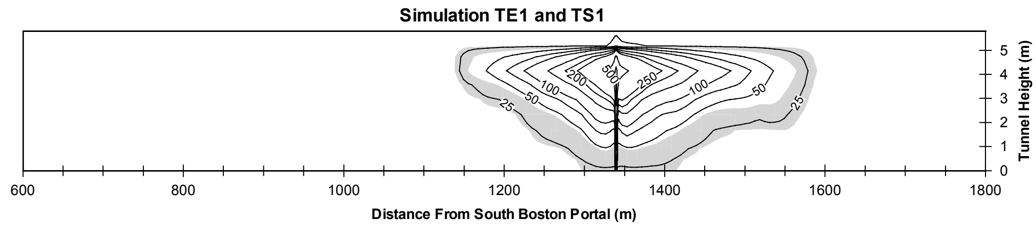

Figure 6. Temperature (°C) and Smoke Distribution at 180 seconds

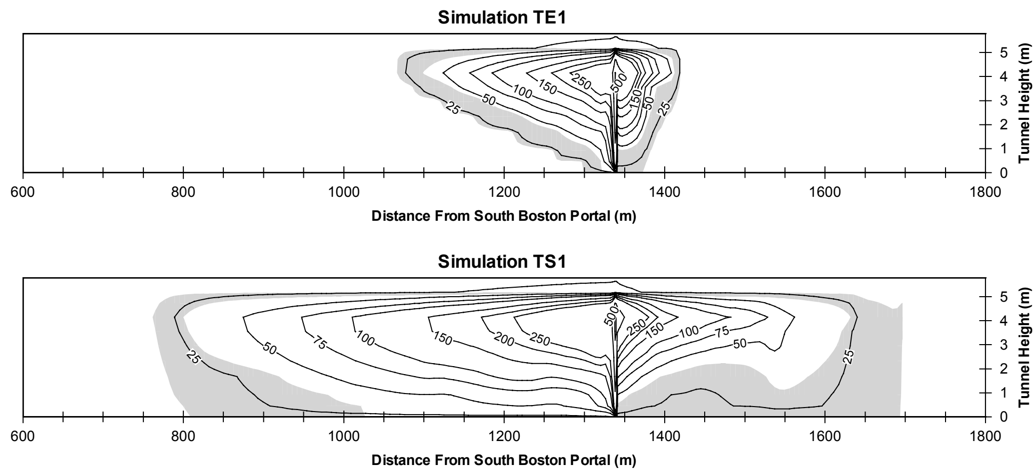

Figure 7. Temperature (°C) and Smoke Distribution at 400 seconds

The results of the transient simulations show that the estimated mode transition point does not provide an equivalent level of protection with either operating mode. A more appropriate transition point would be one in which the benefits of an extraction system in the initial minutes of the fire are balanced by the benefits of the push-pull developed when the zone is operated in supply.

An additional set of transient simulations (TE2 and TS2) was performed with the fire location moved to the interface of zones WB1 and WB2. An evaluation of the bulk velocity plot (Figure 4) indicates that at this location, the exhaust mode would generate relatively low longitudinal flow compared with the supply mode. Since a fire at this location constitutes a worst case scenario for the exhaust mode, it was expected that results from these simulations would help pinpoint the location where the benefits of the two ventilation modes would be effectively equal. The scenario simulated is shown in the following figure.

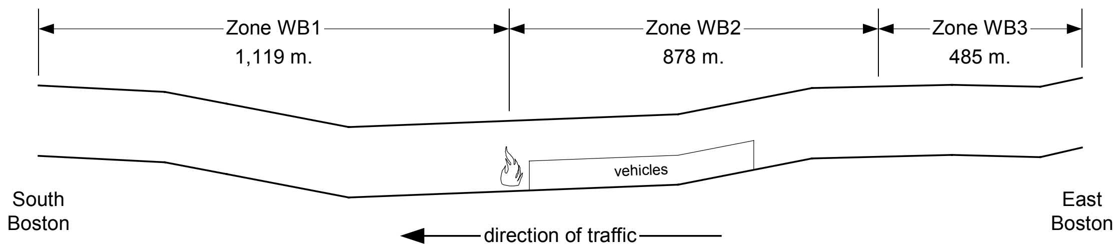

Figure 8. Fire Scenario at New Transition Point

Tunnel conditions at various times are compared in Figures 9 though 11. At 180 seconds, conditions in both simulations are identical and the hazardous region spreads 213 m east and 183 m west of the fire. Both simulations show that the maximum spread of high temperatures and smoke east of the fire occurs about 45 seconds after the emergency mode in the incident zone is activated. At this time, both simulations show that elevated temperatures are stratified and extend approximately 274 m east of the fire. The results from TS2 show that when zone WB2 is operated in supply, the hazardous region is quickly pushed to the unoccupied portion of the tunnel. When the zone is operated in exhaust, however, a 122 m of the hazardous region remains in the occupied portion of the tunnel.

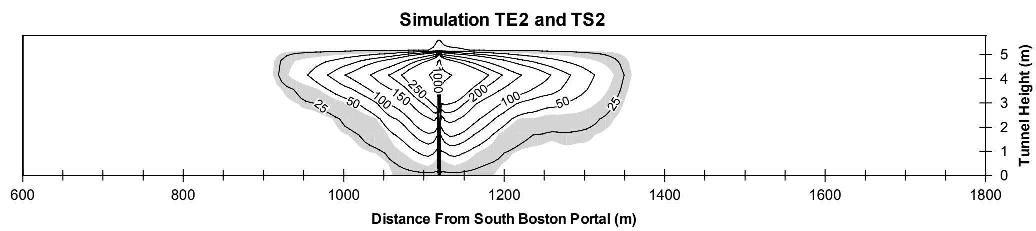

Figure 9. Temperature (°C) and Smoke Distribution at 180 seconds

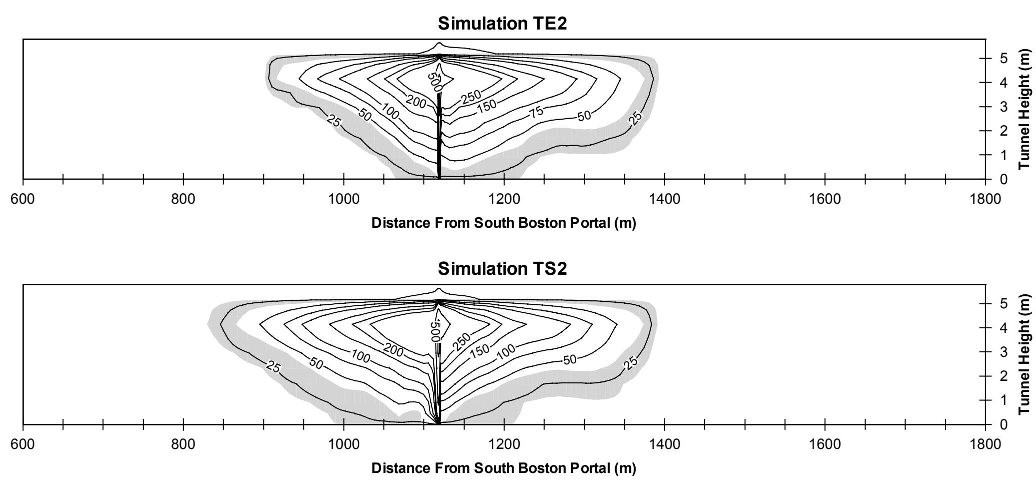

Figure 10. Temperature (°C) and Smoke Distribution at 225 seconds

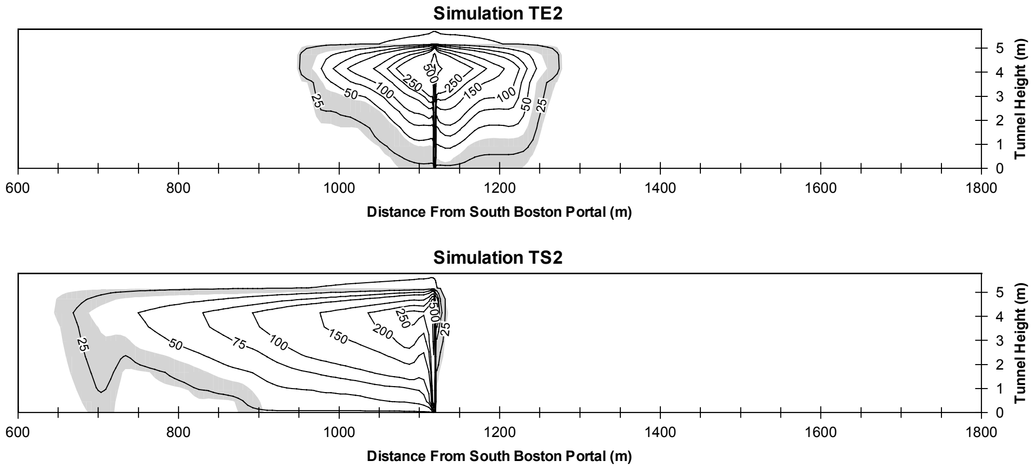

Figure 11. Temperature (°C) and Smoke Distribution at 465 seconds

The transient results for the initially proposed transition point indicated that operating the incident zone in emergency exhaust was much more effective in managing the hazardous effects of the fire than operating the zone in supply. The transient results for the second transition point indicated that the opposite was true. It was therefore concluded that the transition point be located at 1,229 m, the midpoint between the two fire locations evaluated in the analysis. It is estimated that at this location, the benefits of an extraction system in the initial minutes of the fire would be balanced by the benefits of the push-pull developed when the zone is operated in supply.

5.0 Conclusions

While the analysis of only one transition point is presented here, the study performed addressed all seven ventilation mode transition points in the TWT. From the results of this entire analysis, several broad conclusions were reached and taken into account when establishing the recommended locations for transition points. In summary:

1. When the average longitudinal velocity at the fire site is about the same for both operating modes, steady-state simulations showed that the level of protection provided to motorist stopped behind the fire incident were about the same.

2. Extraction in the incident zone tends to be the more conservative option during the initial minutes of a fire when the emergency ventilation system is in a state of transition. With exhaust, smoke is removed from the tunnel, but with supply, the smoke tends to de-stratify and fill the cross-section.

3. Ventilation modes that utilize extraction in the fire zone tend to work best in regions were the grade is unfavorable. However, transient simulations demonstrate that there is a point at which the benefits provided by supply operation surpass those of exhaust operation. This point generally corresponds to where the longitudinal flow at the incident location approaches zero when operating the zone in exhaust. At this location, the longitudinal flow is usually substantial when operating the zone in supply.

4. As conditions in the tunnel transition to steady-state, the recovery of smoke tends to lag that of temperature. This trend is observed with both supply and exhaust operation, but is more pronounced during supply.

5. For fires significantly greater than the design fire (20 MW), operating the incident zone in emergency supply may not force the hazardous region back towards the fire site in a reasonable period of time (or at all), particularly when the grade is unfavorable. The appropriate location for the mode transition point is therefore sensitive to the design fire heat release rate and the expected emergency ventilation system response time.

Based on steady-state results at all seven ventilation mode transition points and transient results at selected points, the emergency operating mode matrix for the entire tunnel was confirmed and/or modified accordingly. The resulting matrix is shown below. The final locations of the mode transition points were adjusted slightly to coincide with locations of milepost markers in the tunnel.

Emergency Ventilation Response Matrix: Ted Williams Tunnel / I-90 Eastbound and Westbound

	Fire Location		**Ventilation Zone Operating Modes**						
	From	**To**	**EB1**	**EB2**	**EB3**	**T-A/D**	**WB1**	**WB2**	**WB3**
I-90 EB	0	850	Exhaust	Exhaust	Exhaust	Exhaust	Press.		
	850	1494	Supply	Exhaust	Exhaust	Exhaust	Press.	Press.	
	1494	2138	Supply	Supply	Exhaust	Exhaust		Press.	Press.
	2138	2481	Supply	Supply	Supply	Supply		Press.	Press.
Ramp T-A/D	0	161	Supply	Supply	Exhaust	Exhaust		Press.	Press.
	161	480	Supply	Supply	Supply	Supply		Press.	Press.
I-90 WB	2481	1666		Press.	Press.		Exhaust	Exhaust	Exhaust
	1666	1183	Press.	Press.			Exhaust	Exhaust	Supply
	1183	700	Press.	Press.			Exhaust	Supply	Supply
	700	0	Press.				Supply	Supply	Supply

Legend
Exhaust – exhaust fans operating at 100%, supply fans at 20%
Supply – supply fans operating at 100%, exhaust fans shut off
Press. – pressurize; supply fans operating at 100%, exhaust fans shut off
Blank cell – designated zone ventilated according to normal ventilation matrix

The locations of the initial and final ventilation mode transition points are shown in Figure 12. The shaded regions identify where the ventilation system operation was modified as a result of this analysis.

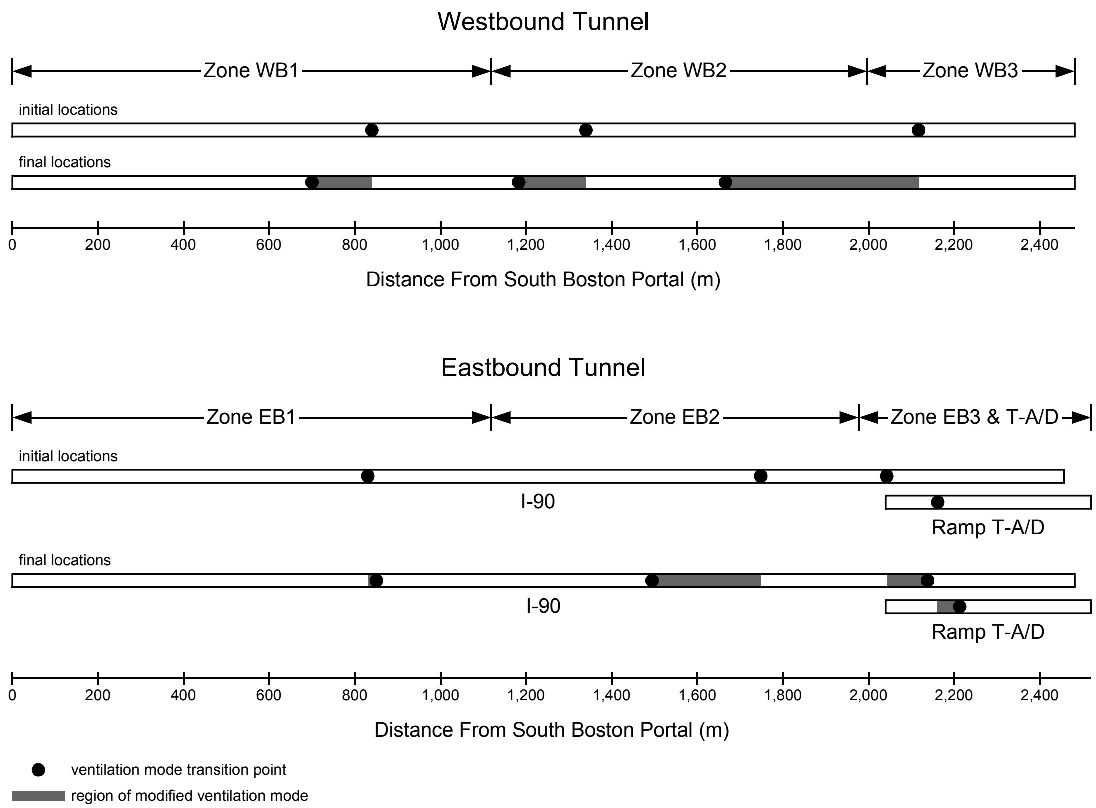

Figure 12. Comparison of Initial and Recommended Ventilation Mode Transition Point Locations

References

1. Innovative Research, Inc./Parsons Brinckerhoff, Inc. 2000. SOLVENT Version 1.0. Innovative Research, Inc./Parsons Brinckerhoff, Inc.