THE APPLICATION OF SOLVENT TO OPTIMIZE THE EMERGENCY OPERATING MODES FOR A ROAD TUNNEL VENTILATION SYSTEM

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Abstract

Emergency operating modes were developed for each tube of the Queens Midtown Tunnel (QMT) and the Brooklyn Battery Tunnel (BBT), for both unidirectional (one-way) and bidirectional (two-way) traffic. Both tunnels are served by a full transverse ventilation system. A one-dimensional cold flow model was used to develop longitudinal velocity profiles for various ventilation system operating modes consistent with smoke control objectives associated with each traffic pattern. Since the appropriate operating mode is a function of the fire incident location, the proposed modes were linked to CCTV camera locations distributed throughout the tunnels. For unidirectional traffic, the final mode transition point locations were selected based on knowledge gained from previous work. The CFD model SOLVENT was used to refine the emergency mode transition point locations for bidirectional traffic to account for the coupled effects of tunnel grade and buoyancy. This paper addresses the study performed for the QMT. A similar study was performed for the BBT.

1.0 Introduction

The Queens Midtown Tunnel (QMT) in New York City is approximately 1.92 km long and extends from midtown Manhattan to Queens. The tunnel is about 60 years old. The tunnel has two tubes, each serving two lanes of traffic. During the morning rush, the North Tube operates unidirectionally (one-way) from Queens to Manhattan and the South Tube operates bidirectionally (two-way). At other times, both tubes operate one-way with the possibility of the North Tube operating two-way during the evening rush in the future. Each tube is served by a full transverse ventilation system comprised of multiple zones with varying supply and exhaust duct capacities.

One of the primary functions of the tunnel ventilation system is to provide a means for controlling smoke movement in the event of a fire incident. The approach used for smoke control varies depending on the type of ventilation system being used and whether the tunnel is serving unidirectional or bidirectional traffic.

In the event of a fire in a tunnel serving unidirectional traffic, it is usually assumed that the traffic ahead of the fire will proceed to the exit portal and the traffic behind the fire will come to a stop. In this case, the ventilation system would be operated to force the smoke and hot gases in the direction of the empty tunnel to provide a clear and safe environment behind the fire for evacuating people and fire fighters.

In the event of a fire in a tunnel serving bidirectional traffic, it is usually assumed that traffic on both sides of the fire will come to a stop. In this case, the ventilation system would be operated to contain the smoke and hot gases as close to the fire as possible to facilitate evacuation in opposite directions.

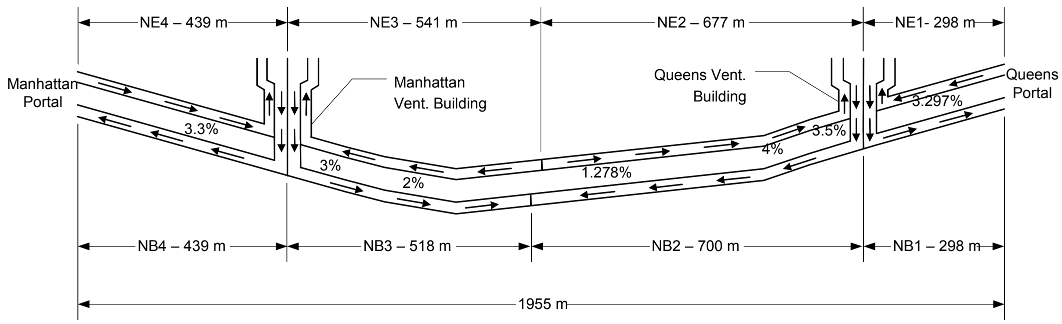
As part of an overall study to rehabilitate the tunnel ventilation system, an analysis was performed to determine the most effective way of operating the existing ventilation system in the event of a tunnel fire. The result of the analysis is an emergency operating mode matrix (or protocol) for each tube. The matrix identifies for both unidirectional and bidirectional traffic how each zone is to be operated as a function of fire location. Since knowing the incident location is critical, each matrix is linked to existing closed-circuit television (CCTV) cameras distributed throughout each tube. This paper addresses the methodology used to develop the emergency operating mode matrix.

2.0 Tunnel and Ventilation System Description

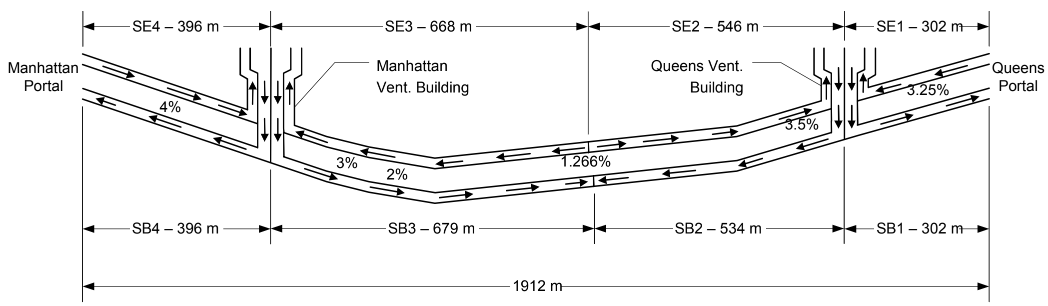
A full transverse ventilation system is used to ventilate the tunnel. The fans are housed in two ventilation buildings. Supply and exhaust ducts, running parallel to the roadway and extending from a ventilation building, serve each roadway. Outside air is supplied through flues located near the roadway curb level. Air is exhausted through ports located in the ceiling. A portion of the roadway that is served by a common duct and fan system is referred to as a zone. There are four ventilation zones in each tube. Figure 1 depicts the tunnel and duct system.

All the fans except for those serving zone 1 of the North tube are equipped with one high-speed motor and one two-speed motor. The fans serving ducts NE1 and NB1 have only one two-speed motor. Each duct has one standby fan and the design capacity is achieved when two fans (one in NE1 and NB1) are operated at high speed.

The QMT duct capacities assumed in the emergency analysis are listed in Table 1. The analysis assumes the flow is distributed uniformly over the length of each duct. The existing CCTV camera locations used in the analysis to determine the limits of regions where a fire incident may be detected is presented in Table 2.



QMT North Tube



QMT South Tube

Figure 1 Tunnel and Duct System

Table 1 QMT Duct Capacities

Ventilation Zone	**Duct**	**Fan Location**	**Number of Fans**	**Fans Operating**	**Duct Capacity (m^3/s)**
North Tube Zone 4	NE4	Manhattan Vent. Building	3	2	120
	NB4		3	2	145
North Tube Zone 3	NE3	Manhattan Vent. Building	3	2	160
	NB3		3	2	163
North Tube Zone 2	NE2	Queens Vent. Building	3	2	134
	NB2		3	2	156
North Tube Zone1	NE1	Queens Vent. Building	2	1	62
	NB1		2	1	54
South Tube Zone 4	SE4	Manhattan Vent. Building	3	2	172
	SB4		3	2	176
South Tube Zone 3	SE3	Manhattan Vent. Building	3	2	180
	SB3		3	2	262
South Tube Zone 2	SE2	Queens Vent. Building	3	2	162
	SB2		3	2	196
South Tube Zone1	SE1	Queens Vent. Building	3	2	119
	SB1		3	2	131

Table 2 Camera Locations in QMT

North Tube

Point	Distance from Manhattan Portal (m)
Manhattan Portal	0
Camera 53	66.4
Camera 51	127.4
Camera 49	223.4
Camera 47B	266.1
Camera 47A	313.3
Camera 45	356.0
Camera 43B	412.7
Camera 43A	450.5
Camera 41	497.7
Camera 39B	546.2
Camera 39A	595.3
Camera 35	726.0
Camera 31	871.1
Camera 25	1115.5
Camera 21	1294.8
Camera 17	1387.4
Camera 15	1502.0
Camera 11	1648.3
Camera 7	1831.2
Camera 3	1951.6
Queens Portal	1955.1

Note:
Cameras 3 to 43 point toward Manhattan.

South Tube

Point	Distance from Manhattan Portal (m)
Manhattan Portal	0
Camera 4A	8.7
Camera 4B	45.6
Camera 6	86.4
Camera 8	191.6
Camera 10	272.0
Camera 12	344.0
Camera 14	404.9
Camera 16	473.5
Camera 18	548.8
Camera 22	725.0
Camera 26	923.1
Camera 32	1151.7
Camera 36	1269.4
Camera 38	1345.2
Camera 40	1418.1
Camera 42	1495.2
Camera 46	1654.6
Camera 48	1769.8
Camera 50	1837.5
Queens Portal	1911.7

Note:
Cameras 4A to 50 point toward Queens.

3.0 Tunnel Modeling

The emergency analysis made use of two different types of modeling tools. TUNVEN is a one-dimensional model used to calculate steady state longitudinal air velocities along the length of a tunnel. SOLVENT uses computational fluid dynamics (CFD) to simulate the interaction between a fire and ventilation system in a road tunnel. The following sections give a brief description of the two models.

3.1 TUNVEN

TUNVEN solves the one-dimensional, steady state tunnel aerodynamic equations. A road tunnel is modeled as a one-dimensional air duct with inflow and outflow at each end and along its length. The tunnel is divided along the length into sections with different ventilation inflow and outflow rates. The program then determines the longitudinal velocity distribution in the tunnel by balancing opposing forces. It takes into account the forces created by pressure differentials at the tunnel portals, vehicle piston action and by addition or removal of air through the ventilation system against opposing forces generated by tunnel wall friction, vehicle resistance and flow entrance and exit losses.

This model is useful in determining which ventilation operating configuration would be most appropriate for an incident in a given location assuming a particular traffic condition. Using the longitudinal flow plots generated with the program's output, the location of null points (zero longitudinal flow) as well as the locations where different ventilation configurations generate equal amount of longitudinal flow can easily be determined. However, this model does not give any information about the impact of a fire or about what may occur when the ventilation system transitions from a normal to an emergency operating mode.

3.2 SOLVENT

SOLVENT is a CFD model for the simulation of fluid flow, heat transfer and smoke transport in tunnels. It was developed specifically for tunnel ventilation applications during Phase IV of the Memorial Tunnel Fire Ventilation Test Program [1] and has undergone extensive validation using the Memorial Tunnel fire tests [2]. In SOLVENT, the fire is represented as a source of smoke and heat. A separate conservation equation is solved for smoke where the total rate of smoke production is calculated from the rate of fuel consumption and the stoichiometric ratio for the fuel, assuming complete combustion.

A unique aspect of SOLVENT is its ability to model the interaction of a tunnel environment with ventilation ducts. A network model, formed by a series of links and nodes, is used to represent the duct system. The network model provides the air supply/extraction rates for the tunnel model. These ventilation rates are used as boundary conditions to the tunnel model. The tunnel model provides the values of pressure and temperature at nodes in the duct network. These boundary conditions in conjunction with the conditions prevailing in the ducts determine the values of pressure, temperature and mass flow rates throughout the duct network.

SOLVENT can determine the unsafe regions of the tunnel, that is, the regions where the hazardous effects of the fire are confined. SOLVENT simulations are useful for comparing the effectiveness of different ventilation configurations and capacities in emergency conditions, and for addressing important aspects of the problem such as the effect of tunnel grade and the impact of delay in invoking emergency ventilation.

4.0 Methodology

The following steps were taken to develop the emergency operating modes for each tube:

1. Develop cold flow velocity profiles for various ventilation system operating modes consistent with the smoke control objectives identified for unidirectional traffic.
2. Develop a unidirectional operating mode matrix from analysis of resulting cold flow velocity profiles coupled with CCTV camera locations.

3. Develop cold flow velocity profiles for various ventilation system operating modes consistent with the smoke control objectives identified for bidirectional traffic.
4. Develop a preliminary bidirectional operating mode matrix from the resulting cold flow velocity profiles.
5. Perform Computational Fluid Dynamics (CFD) simulations at the proposed ventilation mode transition points to address the combined effects of buoyancy and tunnel grade.
6. Perform additional simulations at revised transition point locations as required to confirm performance.

5.0 Analysis and Results

The tunnel air velocities generated by different operating modes were evaluated to determine the appropriate ventilation operation for a given incident location and traffic condition. TUNVEN was used to calculate steady state longitudinal air velocities along the length of each tunnel tube. Mode transition points, i.e., locations where the recommended ventilation operation transitions from one mode to another, were determined from the tunnel air velocity profiles and correlated with CCTV camera positions. For the bidirectional analysis, SOLVENT fire simulations were performed for selected locations to confirm the appropriateness of the transition point.

To identify the operation of a ventilation zone, the zone is designated as either *exhaust*, *supply* or *off*. A designation of *exhaust* means that the ventilation zone is operated at maximum exhaust and zero supply. In other words, (*N*-1) exhaust fans are operated at high speed, where *N* is the total number of fans serving the exhaust duct; fans serving the supply duct are not operated. A similar protocol is followed for a zone with a designation of *supply*. A designation of *off* means that all exhaust and supply fans serving the zone are not operated.

Multiple fire simulations were performed for a fire located at various potential mode transition points throughout the two tubes. The fire heat release rate modeled in each simulation was 20 MW. The heat release rate corresponds to either a bus or large truck fully engulfed in fire.

5.1 Unidirectional Traffic

If a fire occurs in a tunnel serving unidirectional traffic, traffic behind the fire is trapped while traffic ahead of the fire is assumed to proceed to the exit portal. The emergency ventilation mode attempts to push the smoke and hot gases towards the empty end of the tunnel by maximizing the longitudinal flow towards the fire. This is accomplished by operating some ventilation zones in exhaust and others in supply. However, previous work has shown that extraction near the incident is the more conservative option. Additionally, at locations were the tunnel grade is unfavorable, i.e., where the grade favors smoke movement towards the stopped-traffic side of the fire, extraction systems are better able to clear the tunnel of smoke that migrates towards the traffic while the tunnel ventilation system transitions from normal to emergency operation. Accordingly, mode transition points are generally located where the benefits of extraction in the region are balanced by the strong longitudinal flow developed when the incident zone is operated in supply. It should be noted that the transition points represent worse case locations. Moving away from the transition point in either direction results in improved performance by the respective operating mode.

To illustrate the methodology, the recommended unidirectional operating mode matrix for the North Tube is presented in Table 3. The mode transition points are correlated with CCTV camera locations that are used to determine the fire incident location in the tunnel. The longitudinal air velocity profiles generated by each operating mode are presented in Figure 2. A positive value corresponds to airflow moving from left to right. The shaded ovals highlight the recommended mode for a given fire location (as indicated in the mode matrix). As indicated, all modes at the incident locations have been selected to move air from right to left, thus protecting the region where the vehicles are stopped. Extraction in the incident zone is the preferred operation. However, at locations where the grade is favorable, the incident zone is sometimes placed in supply.

Table 3 QMT North Tube – Unidirectional Traffic Emergency Operating Mode Matrix

Fire Location[1]		Mode	Ventilation Zone Operating Mode			
From	**To**		**Zone 4**	**Zone 3**	**Zone 2**	**Zone 1**
0	356	1	Supply	Supply	Supply	Supply
356	595	2	Exhaust	Supply	Supply	Supply
595	871	3	Exhaust	Exhaust	Supply	Supply
871	1,387	4	Exhaust	Exhaust	Exhaust	Supply
1,387	1,955	5	Exhaust	Exhaust	Exhaust	Exhaust

[1] The fire location is measured in meters from the Manhattan portal.

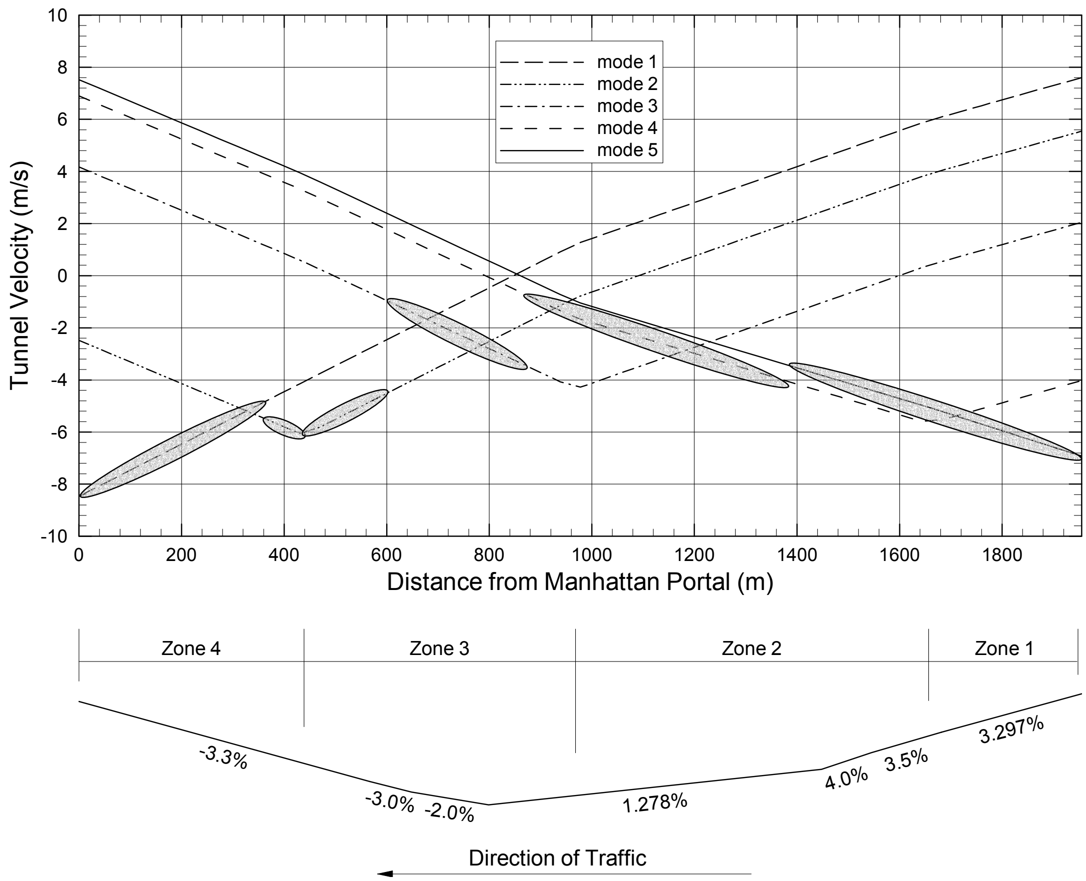


Figure 2 QMT North Tube – Emergency Mode Longitudinal Air Velocity Profiles

5.2 Bidirectional Traffic

In the event of a fire in a tunnel serving bidirectional traffic, traffic is trapped on both sides of the fire. In this situation, the incident zone is always operated in exhaust and the goal of the emergency ventilation is to contain the hazardous effects of the fire as close to the fire as possible. This is accomplished by directing flow towards the fire from both directions thereby creating a zero air velocity point near the fire site. To create as many null points as possible the emergency mode matrices have a number of mode transition points. In situations where it is impossible to generate low velocities at the fire site, the traffic side that has the more lengthy escape path to the portal is prioritized.

To illustrate the methodology, the recommended bidirectional operating mode matrix for the QMT North tube is presented in Table 4. The mode transition points are correlated with CCTV camera locations. The cold flow longitudinal air velocity profiles generated by each operating mode are presented in Figure 3. A positive value corresponds to airflow moving from left to right. The shaded ovals highlight the recommended mode for a given fire location (as indicated in the mode matrix). Except for regions close to the portals, the emergency modes generate low longitudinal velocities at the fire site. Near the portals, it is anticipated that people trapped in vehicles between the portal and the fire will leave their vehicles and exit the tunnel through the adjacent portal by foot while the tunnel is transitioning from normal to emergency operations.

Table 4 QMT North Tube – Bidirectional Traffic Emergency Operating Mode Matrix

Fire Location[1]		Mode	Ventilation Zone Operating Mode			
From	To		Zone 4	Zone 3	Zone 2	Zone 1
0	223	2	Exhaust	Supply	Supply	Supply
223	356	6	Exhaust	Off	Off	Off
356	498	3	Exhaust	Exhaust	Supply	Supply
498	726	7	Exhaust	Exhaust	Off	Off
726	871	5	Exhaust	Exhaust	Exhaust	Exhaust
871	1,116	8	Off	Exhaust	Exhaust	Exhaust
1,116	1,295	9	Supply	Exhaust	Exhaust	Exhaust
1,295	1,648	10	Off	Off	Exhaust	Exhaust
1,648	1,831	11	Supply	Supply	Exhaust	Exhaust
1,831	1,955	12	Supply	Supply	Supply	Exhaust

[1] The fire location is measured in meters from the Manhattan portal.

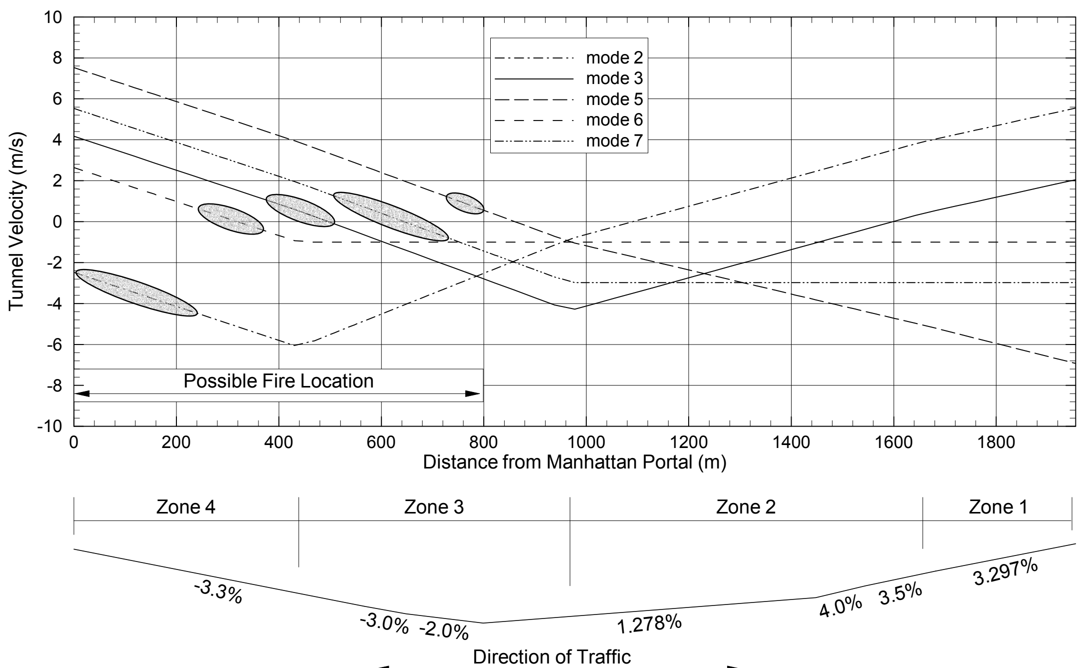


Figure 3A QMT North Tube – Emergency Mode Longitudinal Air Velocity Profiles (for bidirectional traffic and fire located between Manhattan portal and 799 m)

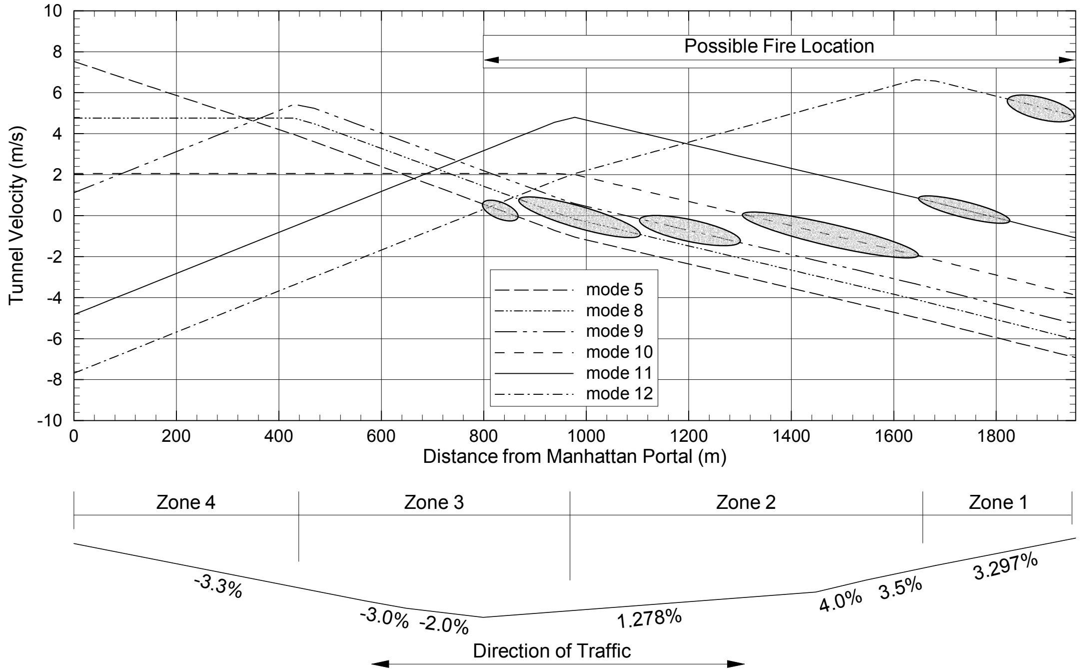


Figure 3B QMT North Tube – Emergency Mode Longitudinal Air Velocity Profiles (for bidirectional traffic and fire located between 799 m and Queens portal)

To evaluate the coupled effects of tunnel grade and buoyancy, steady state CFD simulations were performed at selected locations to refine the matrix. The results of simulations performed for a fire at a mode transition point located 726 m from the Manhattan portal are presented in Figure 4. The CFD simulations have shown that the zero flow point limits the movement of smoke and high temperatures. When compared with the cold flow plot (Figure 3A), the longitudinal air velocity plot shows that the null point has shifted due to buoyancy (for mode 7 the shift is about 91 m to the left and for mode 5 it is about 15 m to the right). The abrupt change in velocity at the fire site reflects the change in air density. The smoke distribution plots illustrate the extent of the hazardous region for the two operating modes recommended for this location. The lightly shaded areas of the plot correspond to the regions where the smoke fronts are located.

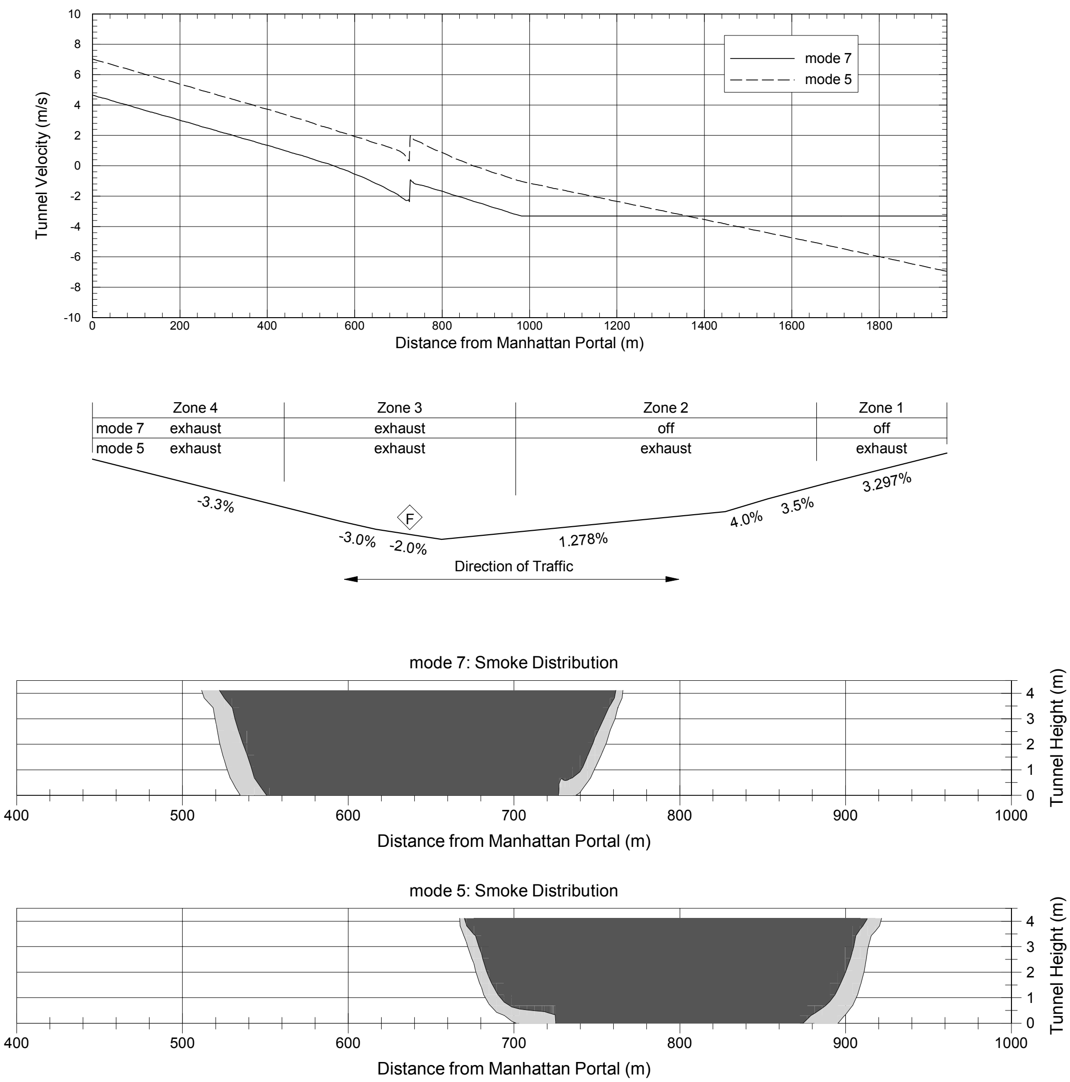


Figure 4 CFD Results for a Fire Located at 726 m

6.0 Emergency Operating Modes

The recommended operation of the ventilation system for the North Tube is presented in Tables 5 and 6. The corresponding camera views related to each mode have been included. To determine the appropriate emergency operating mode, an operator in the control room is required to identify the camera which best views the fire incident. The appropriate table (unidirectional or bidirectional) gives the corresponding mode to be implemented.

Table 5 QMT North Tube – Unidirectional Traffic

Fire Location	Modes	Ventilation Zone Operating Mode			
Camera Views		Zone 4	Zone 3	Zone 2	Zone 1
53, 51,49, 47B, 47A, 45	1	Supply	Supply	Supply	Supply
43B, 43A, 41, 39B, 39A	2	Exhaust	Supply	Supply	Supply
35, 31	3	Exhaust	Exhaust	Supply	Supply
25, 21, 17	4	Exhaust	Exhaust	Exhaust	Supply
15, 11, 7, 3	5	Exhaust	Exhaust	Exhaust	Exhaust

Table 6 QMT North Tube – Bidirectional Traffic

Fire Location	Modes	Ventilation Zone Operating Mode			
Camera Views		Zone 4	Zone 3	Zone 2	Zone 1
53, 51, 49	2	Exhaust	Supply	Supply	Supply
47B, 47A, 45	6	Exhaust	Off	Off	Off
43B, 43A, 41	3	Exhaust	Exhaust	Supply	Supply
39B, 39A, 35	7	Exhaust	Exhaust	Off	Off
31	5	Exhaust	Exhaust	Exhaust	Exhaust
25	8	Off	Exhaust	Exhaust	Exhaust
21	9	Supply	Exhaust	Exhaust	Exhaust
17, 15, 11	10	Off	Off	Exhaust	Exhaust
7	11	Supply	Supply	Exhaust	Exhaust
3	12	Supply	Supply	Supply	Exhaust

7.0 Conclusions

1. For a tunnel that serves both unidirectional (one-way) and bi-directional (two-way) traffic, emergency operating modes should be developed to address not only fire location but also the type of traffic, since the intended evacuation path is different for each case.

2. Appropriate emergency operating modes for a multi-zoned transverse ventilation system can be developed using a one-dimensional cold flow model that can reasonably predict the longitudinal velocity in the tunnel as a function of ventilation system operation.

3. For unidirectional traffic, locations for mode transition points should consider the expected migration of smoke prior to the ventilation system achieving delivery of the emergency flow rates. This should be based on the expected size and growth rate of the design fire, tunnel grade, and realistic delays for detecting an incident and implementing the appropriate emergency operating mode. The extent of smoke migration can be evaluated by performing CFD simulations at selected locations in the tunnel.

4. For bidirectional traffic, the emergency operating mode attempts to locate the longitudinal velocity null point as close to the fire as possible. Since the null point is sensitive to tunnel grade, the buoyancy effects of the fire, and the possible reduction in performance of the exhaust duct in the region of the fire due to elevated temperature, CFD simulations are required to refine the mode transition point locations.

References

1. Bechtel/Parsons Brinckerhoff, Memorial Tunnel Fire Test Ventilation Program-Phase IV Report, prepared for Massachusetts Highway Department/Federal Highway Administration, 1999.

2. Bechtel/Parsons Brinckerhoff, Memorial Tunnel Fire Test Ventilation Program, Comprehensive Test Report, prepared for Massachusetts Highway Department/Federal Highway Administration, 1995.