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PERFORMANCE INVESTIGATION OF EMERGENCY VENTILATION STRATEGIES IN A NEW SECTION OF A ROAD TUNNEL

Ahmed Kashef, Noureddine Bénichou National Research Council of Canada

Alexandre Debs, Ministère des Transports du Québec, Canada

ABSTRACT

The National Research Council of Canada (NRC) conducted a study to evaluate the effectiveness of the current emergency ventilation system (EVS) to control smoke and hot gases originating from fires in a new section of a road tunnel in Montréal, Canada. The project uses the Computational Fluid Dynamics (CFD) technique for simulating smoke movement behaviour. Data from full-scale tests were used to verify the CFD model. The study provided recommendations to improve the effectiveness of the EVS.

The study findings indicated that the effectiveness of the EVS was significantly affected by large pressure losses in the ventilation fans plenum and by the obstruction of large concrete beams to airflow. To improve the effectiveness of the ventilation fans, the study recommended the introduction of a ducting system to control airflow losses and to better direct airflow in such a way as to avoid impacting on the beams. With the high ceiling in this section of the tunnel, the possibility of collecting and storing smoke and hot gases at high elevations was investigated by operating the EVS in exhaust mode.

1 INTRODUCTION

A study was conducted at NRC to evaluate the performance of the EVS in a newly constructed section of the Montreal Ville-Marie road tunnel in the event of a fire. The study aimed at: assessing the ability of in-place emergency ventilation strategies to control smoke spread and minimize its impact on tunnel users; recommending guidelines to maximize the intervention effectiveness; and allowing future development of an automatic ventilation system.

The study included two phases: a numerical and an experimental phase. The numerical phase used the Fire Dynamic Simulator (FDS)[1] CFD model to simulate smoke spread in the tunnel section. The experimental phase was used to calibrate and partially verify the CFD model and to provide the necessary initial and boundary conditions.

1.1 Tunnel Geometry and Ventilation System

The study was conducted in the new section that was recently added to the Ville-Marie road tunnel, located under the Palais des Congrès. The section was 305 m long and had five lanes (Figure 1). The new section started at Chainage (CH) 16+65 and extends up to the East Portal at CH 9+00. The traffic moved from the West to the East exiting the tunnel at the East Portal. The section was characterized with large ceiling heights and a positive sloped floor towards the East

Portal. The clear height of the tunnel changes as the floor of the tunnel has an up-slope from the West to the East. It also had three large cross-beams: B1, B2, and B3.

The section ventilation was provided by a longitudinal system composed of three sets of fans. The first set consisted of fans 088020/088022/088024 and provided air through wall vents (Figure 1). Fans 088021/088023/088025 composed the second set that provided air through ducts (Figure 1). The vents and ducts of both sets of fans are located at the vertical wall at CH 16+65. The third set is comprised of fans 098081/098083 and provided fresh air through vents located in the ceiling area between CH 19+00 and CH 16+65 of the old section of the tunnel.

1.2 Fire Tests

Fire tests were conducted using a propane burner system developed by NRC[2] (Figure 2). The fire source was portable and allowed for different fire sizes (in the 1 to 5 MW range) simulating a small vehicle fire. It also included safety systems for immediate shutdown. All instrumentation was portable and readily set-up in a limited time frame.

Four full-scale in-situ fire tests, corresponding to four ventilation scenarios, were conducted with the fire fixed at one location. The fire sizes varied between 2 to 4 MW depending on the activated ventilation scenario so as to minimize the damage to the tunnel structure and its components, by limiting the temperature at the tunnel ceiling below 100°C, and to produce reliable data for the calibration of numerical models.

Airflow measurements were conducted to develop the boundary conditions for the CFD model simulations. In addition, the ranges of airflow conditions at the East portal were established.

Temperature and optical smoke density measurements were measured at three locations downstream of the fire with 26 points of measurements. All measurements were taken at a vertical axis positioned at the centreline of the tunnel cross-section. Upstream was defined in the context of this report as the direction from which the traffic entered the tunnel. Air speed was measured at the East Portal, at CH 19+00, at the fan vents and ducts (CH 16+65), at the Beams B1, B2 and B3 and at the fire locations.

2 NUMERICAL SIMULATIONS

CFD models solve the complex differential equations describing the conservation of mass, momentum, enthalpy, species, etc. within the physical domain of interest. These models simulate the overall fire environment for a specific fire scenario including ambient conditions prior to a fire. The space and time dimensions are discretized into finite intervals and fluid variables such as temperature, velocity, gas composition and pressure are computed at a finite number of locations at the grid points as a function of time.

The Fire Dynamic Simulator (FDS) model[1] employed the Large Eddy Simulation (LES) approach, to solve the large scales of motion and model the small scales that are assumed to be universal. FDS solves a form of high-speed filtered Navier-Stocks equations valid for a low-speed (low Mach number) buoyancy-driven flow. In FDS, fire is represented using the “mixture fraction-based” combustion model in which large-scale convective and radiative transport phenomena are directly simulated and the physical processes occurring at small length and time scales are approximated (the model does not simulate the actual combustion process).

A representative fire heat-release rate of 20 MW corresponding to a bus or truck on fire was used. The fire was modelled as an equivalent gasoline pool[3] with an area of 8 m^2 and CO_2, CO and smoke flow production rates of 1.5 kg/s, 0.077 kg/s, and 60 m^3/s, respectively.

Six fire scenarios were simulated, four of which were used to investigate the effectiveness of the EVS operating in supply mode. The remaining two simulations were conducted with the Fan Sets 1 and 2 operating in exhaust mode. Fan Set 3 operated in supply mode at all times acting as a smoke barrier preventing smoke from re-entering the old section of the tunnel against the traffic.

Table 1 Activated Fire Scenarios

EVS Mode	Fire Scenario	Fire Location	Ventilation Scenario	Set 1		Set 2		Set 3	
				Mode	Capacity m^3/s	Mode	Capacity m^3/s	Mode	Capacity m^3/s
Supply	Ufans	CH16+65	VentSC 1	Supply	255	Supply	255	Supply	234
	Ubeams	CH15+53	VentSC 1	Supply	255	Supply	255	Supply	234
	CH13	CH13+65	VentSC 1	Supply	255	Supply	255	Supply	234
	CH10	CH10+48	VentSC 1	Supply	255	Supply	255	Supply	234
Exhaust	Ubeams	CH15+53	VentSC 2	Exhaust[1]	155	Exhaust[1]	155	Supply	234
	CH13	CH13+65	VentSC 2	Exhaust[1]	155	Exhaust[1]	155	Supply	234

Set 1: fans 088020/088022/088024
Set 2: fans 088021/088023/088025
Set 3: fans 099081/099083
[1]: 60% of Set capacity in the normal mode (supply mode)

2.1 Simulations of the EVS in Supply Mode

Four fire locations were simulated with the EVS operating in the supply mode: one located at the interface of the old/new tunnel section at CH 16+65 (hereafter called "UFans" fire scenario); under the second beam at CH 15+53 (hereafter called "UBeams" fire scenario); at CH 13+36 (hereafter called "CH13" fire scenario) and at CH 10+90 (hereafter called "CH10" fire scenario). The locations were selected to cover most of the possibilities of fire occurring in this section.

In-situ fire tests revealed that ventilation scenario VentSc 1 (Table 1) was the most effective scenario among all tested ventilation scenarios. VentSc 1 produced the largest airflow speed pushing smoke downstream of fire and out of the East Portal. Therefore, VentSc 1 was used to investigate the efficiency of using the EVS in supply mode during the numerical simulations of the four fire locations. For Ventilation VentSc 1, the three sets of fans operated in supply mode.

Figure 3 shows the velocity vectors of the flow field, along a vertical plane through the middle of the tunnel section, resulting from activating Ventilation Scenario VentSc 1 with no fire. The length of vectors range from short for a slower flow to long for a faster flow. The airflow is fast over the beams close to the ceiling towards the East portal and mostly reversed under the beams. Close to the wall of the tunnel and away from the fans, most of the airflow is reversed with the dominant airflow directed from East to West (Figure 3).

It is important to maintain a minimum airflow velocity in the tunnel to prevent smoke backlayering. The critical velocity [3] depends on tunnel geometry and fire size. For this section of the tunnel, the critical velocity corresponding to a fire heat release of 20 MW is about 1.7 m/s. Other studies have indicated that with a heat release rate not exceeding 100 MW, an airflow velocity of 3 m/s is sufficient to prevent smoke backlayering [4,5].

Ufans Fire Scenario: Figure 4 presents the burning bus location and the resulting velocity vector field. The flow field was modified due to the fire and less area of reversed flow exists under the beams. Figure 5 shows the resulting airflow distribution for this scenario. The resulting visibility [6] after the simulation reached a steady-state condition is shown in Figure 6. From the figure, no backlayering of smoke in the old section of the tunnel was observed. Moreover, all smoke moved towards the East Portal in the traffic direction. The set of ceiling fans 098081/098083 created an air curtain that prevented smoke from moving upstream of the fire.

Ubeams Fire Scenario: Figure 4 presents the burning bus location and the resulting modified velocity vector field. The flow field was modified due to the fire and became more turbulent in the area around the beams. The modified flow distribution is shown in Figure 5. The steady-state visibility is shown in Figure 6. The figure indicated that backlayering of smoke occurred up to a distance of about 20 m upstream of the fire.

CH13 Fire Scenario: Figure 4 presents the resulting velocity vector field for this Scenario near the old/new sections interface. The flow field was similar to that for the case with no fire (Figure 3). The steady-state visibility is shown in Figure 6. From the figure, smoke backlayering occurred up to a distance of about 70 m upstream of the fire.

CH10 Fire Scenario: Figure 4 presents the resulting velocity vector field. Fresh air was mainly drawn from upstream of the fire. The blockage due to a road signage at CH 12+50 (198 m from CH 19+00) created an area of reversed flow close to the ceiling upstream of the fire. Downstream of the fire the airflow is mainly pushed towards the East Portal. Figure 5 shows the resulting airflow distribution for this case. The average airflow velocity at the fire was about 2 m/s greater than 1.7 m/s indicating favourable conditions for avoiding backlayering phenomena. The steady-state visibility is shown in Figure 6. The figure indicated that smoke backlayering occurred up to a short distance of about 30 m upstream of the fire as a result of the reversed airflow in this region. In this region, the average visibility Drops to about 15 m.

2.2 Simulations of the EVS (Fan sets 1 and 2) in the Exhaust Mode

As demonstrated in the previous section, operating the EVS in the supply mode produced untenable conditions downstream of the fire for the two fire scenarios: UBeams and CH13. To explore the possibility of maintaining smoke and hot gases at high elevations for these two fire locations, the two sets of fans, SET 1 and SET 2 were operated in the exhaust mode (VentSc 2, Table 1).

Ubeams Fire Scenario: Figure 7 presents the modified flow distribution for this Scenario. Fresh air was drawn to the fire location from both upstream and downstream of the fire. In this case the ceiling jet flow was mainly directed towards the exhaust fans. The steady-state visibility is shown in Figure 8. The smoke and hot gases were kept at a level above the three Beams. This is confirmed from Figure 9. A 20 m visibility or higher was maintained upstream the fire.

CH13 Fire Scenario: Figure 7 presents the flow distribution associated with this scenario. A larger portion of the fresh air was drawn to the fire location from upstream than that from downstream of the fire. In this case the ceiling jet flow was directed both upstream and downstream of the fire. The existence of the grid of beams at the ceiling slows the movement of the ceiling jet flow (Figure 9). The cross-sectional area of the tunnel decreases towards the East portal due to the slope of the floor. As a result, the airflow accelerated as it moved towards the East portal which pushed the smoke and hot gases towards the East (downstream of the fire). As a result, smoke and hot gases were kept at a level above the three Beams (Figure 9). Furthermore, a 20 m visibility or higher was maintained upstream of the fire (Figure 8).

3 DISCUSSION AND CONCLUSIONS

During the fire tests with the fire source at CH 13+36 and using a ventilation scenario in which the EVS operated in the supply mode, no backlayering was observed. However, the fire size was limited to a maximum of 4 MW. The capability of the EVS in removing smoke and hot gases was investigated for a larger fire of 20 MW fire size (equivalent to a bus on fire).

In general, the use of the EVS in supply mode was not effective in maintaining tenable conditions when the fire source was located anywhere in the tunnel up to CH13+65. However, at locations further away from the fans where the airflow speed is greater than the critical velocity, the supply mode may be used to maintain tenable conditions upstream of the fire.

With the EVS Operating in supply mode (VentSc 1), four fire locations were simulated: one located at the interface of the old/new tunnel section Under Fans; another under beam B2, the third at CH 13+36, and the fourth at CH 10+90. The presence of Beams B1, B2, and B3 in the new section of the tunnel significantly obstructed the supplied ventilation airflows and created strong turbulent flow conditions around the three beams inhibiting the airflow from moving towards the East Portal.

The phenomenon of backlayering was predicted for the two fire scenarios: Under Beams and CH13. For these two fire locations and for a 20 MW fire size, the EVS should provide a minimum average velocity of 1.7 m/s upstream of the fire source to prevent backlayering. For fire scenario CH10, the average airflow velocity at the fire is 2 m/s greater than the critical velocity indicating favourable conditions for avoiding backlayering. Backlayering of smoke occurred for a short distance of about 30 m upstream of the fire where the average visibility dropped to about 15 m.

With the EVS Operating in Exhaust mode, two fire scenarios were simulated: Under Beams; and CH13 under the VentSc 2 ventilation scenario. For the fire scenarios Under Beams and CH13, the smoke and hot gases were kept at a high level upstream of the fire where a 20 m visibility or higher was maintained.

It is believed that the performance of the ventilation fans is significantly affected by large pressure losses in the plenum of fans 088020/088022/088024 and due to the obstruction of beams B1, B2, and B3. To improve the efficiency of the EVS, airflow losses should be minimized. This could be achieved by using a proper ducting system that better directs the airflow to avoid impacting on beams B1, B2, and B3. Another possible remedial measure is to install jet fans under Beams B1, B2, and B3 to enhance the airflow in this section.

Although the traffic effect was not studied and since the ventilation is provided longitudinally in this section, it was recommended that the effect of traffic on the EVS systems performance be considered especially in areas where the height of the tunnel cross-section decreases (close to the exit portal).

With the high ceiling of this section of the tunnel, the possibility of keeping smoke and hot gases at high elevations was investigated by operating the EVS in the exhaust mode. In this case, the activated ventilation scenarios were able to maintain a tenable environment in the tunnel upstream of the fire up to the fire source being located at CH13+65. At locations further away from the exhaust fan, the exhaust mode may not be effective in maintaining tenable conditions in the tunnel.

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