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Optimization of Emergency Ventilation Strategies in a Roadway Tunnel

ABSTRACT

In order to evaluate the effectiveness of in-place emergency ventilation strategies to control smoke spread in the event of a fire in a section of a roadway tunnel, both numerical and experimental studies were performed. The experimental study was conducted to provide the necessary initial and boundary conditions for the numerical phase of the investigation. A fire heat release rate of 1 MW was used in all fire tests. This fire heat release rate was selected to minimize the risk of damage to the tunnel and its associated systems while producing reliable data for visualizing the smoke movement in the tunnel. The numerical study used Computational Fluid Dynamics, Fire Dynamic Simulator version 4.0 to investigate smoke removal in the tunnel for large fire of 30 MW (bus or truck on fire). In total, four field fire tests and seven numerical simulations were conducted. Based on the study results, recommendations were made to optimize the ventilation scenarios in the tunnel section. This article presents the details of the study as well as the recommendations made.

KEYWORDS: Emergency ventilation strategies, roadway tunnels, fire incidents, visibility, smoke backlayering, computational fluid dynamics, field fire test, Fire Dynamics Simulator.

INTRODUCTION

Emergency Ventilation System (EVS) is an important element of the protection system in tunnels. The main objective of the EVS is to provide safe egress route and secure rescue operation by maintaining tenable environment in the tunnel. This is achieved by ensuring acceptable levels of air temperature, heat fluxes, toxicity, and visibility in the tunnel roadways and egress routes. Depending on the specific application, criteria should be selected for the tenability design. Methods of controlling contaminants and smoke from a fire in a tunnel using EVS include: inducing longitudinal airflow, smoke extraction and smoke dilution. In the event of unwanted fire, a strategy of smoke removal, which consists of selecting a sequence of fans operation, should be immediately implemented to control the phenomenon of “backlayering”. The backlayering phenomenon is defined as the situation in which the smoke moves against the airflow provided by the ventilation system upstream of the fire creating an environment that poses a danger to both tunnel users and emergency responders. The strategy could be modified with the arrival of the fire department to facilitate access to the fire location.

In the event of a fire, the airflow in a tunnel is modified and becomes highly unsteady. The modification of the airflow is due to the fire itself, the operation of the EVS, and the change in the traffic flow in the tunnel. The smoke progress and its degree of stratification depend mainly on the airflow in the tunnel. With no airflow in the fire zone, the buoyant smoke travels upwards and then moves symmetrically on both sides of the fire [1]. As fire grows, smoke travels away from fire releasing its heat at the tunnel ceiling and walls due to the combined effect of convective and radiative heat exchange and the mixing between the smoke and the fresh air layer. As such, smoke cools down and loses its stratification. As a result, smoke layer drops down and starts to fill the tunnel causing a much lower visibility. Other parameters that affect the smoke flow [1] and stratification are: heat release rate, tunnel length, cross-section and grade, traffic flow, and meteorological conditions. Establishing airflow requirements for roadway tunnels and consequently the capacity of the EVS is a challenging task due to the difficulty of controlling many variables (e.g. changes in traffic patterns and modifications to the tunnel).

A study has been conducted at the National Research Council of Canada (NRC) to evaluate the performance of the EVS in the event of a fire in a roadway tunnel. This study aimed at assessing the ability of in-place emergency ventilation strategies to control smoke spread and minimize its impact on the tunnel users. Both numerical and experimental studies were performed to achieve this objective. This article describes the conducted in-situ fire tests and presents test measurements used to provide the initial and boundary conditions for the Computational Fluid Dynamics (CFD) simulations. The CFD simulations were conducted using a fire load of 30 MW (a bus or truck on fire). With the restriction of carrying hazardous goods into the tunnel, this fire load represents a rational design fire [2]. Based on this study, optimized ventilation strategies were identified for the investigated tunnel section.

Tunnel Description and Ventilation System

The tunnel under investigation, constructed in 1974, crosses the heart of a downtown area over a 2.16 km length in the east-west direction. This tunnel is composed of two principal tubes and involves a complex geometry with different numbers of lanes (1 to 5 lanes), slopes, natural ventilations (favoring or opposing smoke clearance), type of mechanical ventilation systems (semi-transversal or longitudinal), and cross-section heights. The tunnel constitutes a major underground system from the point of view of traffic and structural complexity. The tunnel includes five ventilation towers approximately 300 m to 460 m apart. Tower 9 is used as a control and monitoring centre for the tunnel. In order to properly assess the performance of the EVS of the tunnel, it is important to study the different combinations of the existing fans, and their effects on controlling the backlayering phenomenon and removing smoke and hot gases.

This paper focuses on a section of the tunnel, which is about 853 m long. This section extends from CH 17+00 (east portal of Tube A) to CH 45+00 (west portal of Tube C) (Figure 1). In the context of this paper, distances along the tunnel are expressed in Chainages (CHs). The Chainage CH $n + aa$ is the distance from datum, where n is the distance in hundreds of feet and aa is the distance in feet (two digits). For example CH 17 + 30 means the distance from the datum equals 1730 ft (527.3 m). Traffic travels from the east towards the west. The height of the tunnel section is approximately 5.0 m and has a width of: (a) 22.0 m (5-lanes, Tube A: from CH 17 + 00 to CH 23 + 00), (b) 12.8 m (3-lanes, Tube A: from CH 23 + 00 to CH 25 + 00), (c) 9.8 m (2-lanes, Tube C: from CH 23 + 00 to CH 34 + 84), (d) 12.8 m (3-lanes, Tube C: from CH 34 + 84 to CH 38 + 00), (e) 5.0 m (1-lane, Tube C: from CH 38 + 00 to CH 45 + 00), and (f) 9.8 m (2-lanes, Tube D: from CH 38 + 00 to CH 41 + 00) (Figure 1).

The mechanical ventilation system in this section of the tunnel is a semi-transverse system that consisted of a series of reversible fans as listed in Table 1. As shown in Table 1, some fans have only one vent (WF2, WF3, WF7, WF8, WF9). Some other fans have many vents distributed in the ceiling (CF1, CF2, CF3, CF4, CF5), north wall (WF4), south wall (WF1, WF6), and north and south walls (WF4). These fans were installed in 1974. As such, fan capacities in both normal and reverse modes were measured during the field tests in order to evaluate their current efficiencies. The measured flow rates were used in the numerical simulations as boundary conditions.

EXPERIMENTAL STUDY

Four full-scale fire tests were conducted, using a clean-burning propane system that produces minimal visible smoke, for a fire heat release rate (HRR) of 1 MW. The fire HRR was selected to minimize the risk of damage to the tunnel and its associated systems while producing reliable data as initial and boundary conditions for the numerical model [3]. Artificial smoke was added for visualization purposes. The first two fires were conducted in the straight region of the tunnel at CH 28+50. The other two fires were conducted in the curved region at CH 36+00. At each of the two fire locations, two ventilation scenarios were activated. The fire locations were selected to be representative

of the most critical spots of fire incident in the tested tunnel section. The description of these four ventilation scenarios and the activated fans are listed in Table 3.

A team of 12 persons conducted the tests including collection of temperature, airflow and smoke optical density (SOD) data. The SOD indicates the level of smoke obscuration. The higher the value of smoke optical density, the higher the level of obscuration and the lower the level of visibility in the tunnel. The SOD values were measured using smokemeters, in which, a light beam is produced from a light source and the intensity of light remaining after it has passed through the path length is measured by a photo cell unit. The measured voltage output of the photo cell were calibrated to give directly the SOD as follows [4]:

$$SOD = -\frac{\log_{10} T}{x} \quad (\text{Eq. 1})$$

where:

$$\begin{aligned} \delta &= \text{optical density per unit distance, m}^{-1}; \\ T &= \text{transmittance ratio, dimensionless;} \\ x &= \text{distance of light travel path, m.} \end{aligned}$$

The SOD values can then be used to calculate the visibility as follows:

$$VIS = \frac{C}{2.303 SOD} \quad (\text{Eq. 2})$$

where C is the proportionality constant. The instrumentation positions for all four tests are listed in Table 2. Drop 4 was located upstream of the fire while Drop 1 through Drop 3 were located downstream of the fire. Upstream of the fire denotes the direction from which the traffic flows. At Drop 1, vertical and horizontal thermocouple trees were installed. The vertical thermocouple tree was located at 1.5 m downstream of the fire in scenarios CH28SCA and CH28SCB, and at the fire location in scenarios CH36SCA and CH36SCB, to measure the fire plume centerline temperatures. In this tree, five thermocouples were distributed at 1.0 m intervals starting from the tunnel ceiling. A horizontal thermocouple tree was also installed at Drop 1 to measure the tunnel ceiling temperatures above and downstream of the fire. In this tree, seven thermocouples were distributed at 1.5 m intervals along the tunnel ceiling. The ceiling temperature measurements at Drop 1 was used to select the proper fire HRR to minimize the risk of damage to tunnel structure and its associated systems. It was found that a fire HRR of 1 MW limited the temperature at tunnel ceiling to be below 150°C. This fire HRR was used in the four fire tests.

One vertical thermocouple tree was installed at each of Drop 2 through Drop 4. In each tree, six thermocouples were distributed at 1.0 m intervals starting at the tunnel ceiling. Two smokemeters were installed on each tree at elevations of 1.4 and 3.6 m from the tunnel ceiling. During the course of each fire test, the trees at Drop 2 through Drop 4

were moved across the tunnel width to record the measurements at the tunnel cross-section centerline and one-quarter points.

The airflow measurements were taken at all vents of the fans in both normal and reverse modes of operation using a handheld vane anemometer. Table 1 shows the number of vents and their location for each activated fan. Additionally, airflow velocity measurements were made at different locations with and without fire. Measurements of natural airflow were also recorded (no ventilation). These measurements provided the input data for the CFD simulations.

For a fire at CH 28+50 (located in the straight region of the tunnel), the ceiling fans CF1 and CF2 were operated in supply mode, and the wall fans WF1, WF2, and WF3 were operated in exhaust mode in fire scenario CH28SCA. Fire scenario CH28SCB is similar to CH28SCA, except for ceiling fans CF1 and CF2 being activated in exhaust mode. For a fire at CH 36+00 (located in the curved region of the tunnel), the wall fan WF4 was operated in supply mode and wall fans WF5 through WF9 were operated in exhaust mode in CH36SCA. In fire scenario CH36SCB, same set of fans was activated with fan WF4 being operated in exhaust mode.

The following observations were made from the data analysis of the four field fire tests [3]:

- The airflow velocity was measured before the fire tests to record the natural ventilation. The prevailing wind speed was measured to be about zero at all portals.
- The ventilation scenarios in the first two fire tests at CH 28+50 (CH28SCA and CH28SCB) resulted in a small negative airflow upstream of the fire (negative values indicate airflow same to the traffic flow). This flow could not hold the movement of the smoke front and as a result, a short distance of smoke backlayering close to the ceiling was observed for these ventilation scenarios (Figure 3). However, most of the smoke traveled downstream of the fire for CH28SCA and CH28SCB.
- In the curved region of Tube C, the airflow supplied by the distributed lower vents in the north and south walls resulted in a net longitudinal velocity component of about zero hindering the movement of smoke in the longitudinal direction (Figure 3). Moreover, both the lateral vents and tunnel curvature induced turbulence that cooled down the hot buoyant smoke and enhanced its dilution. As a result, the SOD values both upstream of the fire (at Drop 4) and downstream of the fire (at Drop 3) were significantly higher and it took a much longer time to clear the smoke than that for a fire at CH 28+50 (straight region of Tube C) (Figure 5).
- For fires at CH 28+50, the maximum ceiling temperature was generally measured at about 1.5 – 4.5 m downstream of the fire (the fire plume was tilted toward the downstream of the fire). For fires at CH 36+00, the fire plume was approximately vertical as a result of a small longitudinal airflow velocity. The highest maximum ceiling temperature was measured in CH36SCA (181°C), while CH28SCA produced the lowest maximum ceiling temperature (127°C) (Figure 3).
- Close to the fire (Drop 1), the highest maximum temperature occurred at an elevation of about 3.0 m from the ceiling (~flame height) for fires at CH 36+00 and at the ceiling for fires at CH 28+50 (Figure 4a). The highest maximum temperature at

Drop 1 (385°C) was measured in CH36SCA, while the lowest maximum temperature (82°C) was measured in CH28SCA. The maximum temperature was the maximum value measured over the steady-state portion of the data for each test at a certain location of measurement.

- At about 50 m upstream of the fire (Drop 4) and downstream of the fire (Drop 2), vertical temperature profiles showed stratification with a hot layer near tunnel ceiling, and a cold layer with temperature close to ambient for all tests (Figure 4b, d).
- At about 100 m downstream of the fire (Drop 3), stratification with a relatively small hot layer near tunnel ceiling was observed only for CH36SCA and CH36SCB (Figure 4c).
- The maximum SOD measurements were recorded mostly by the smokemeter located near the ceiling, indicating that most of the smoke was located close to the tunnel ceiling (Figure 5).
- Maximum SOD measurements upstream and downstream of the fire were, in general, the highest for CH36SCA (Figure 5).

Based on the in-situ fire tests results and observations, the next step of the study was performed by conducting CFD numerical simulations using a large fire HRR of 30 MW. The experimental part provided the necessary initial and boundary conditions for the numerical simulations. As well, based on the field observations some ventilation scenarios were revised in order to improve its smoke extraction performance.

NUMERICAL STUDY

The current study employs the Fire Dynamic Simulator (FDS) version 4 CFD model [6] for the simulation of the behavior of the smoke originating from fires in the tunnel section. FDS is based on the Large Eddy Simulation approach and solves a form of high-speed filtered Navier-Stokes equations valid for low-speed buoyancy driven flow. These equations are discretized in space using second order central differences and in time using an explicit, second order, predictor-corrector scheme. In FDS, fire is represented using the “mixture fraction-based” combustion model.

FDS has been the subject of numerous validations [7]. The validation efforts included: comparison with full-scale tests conducted specifically for code evaluation, comparison with engineering correlations, comparison with previously published full-scale test data, comparison with standard test, and comparison with documented fire experience. Kashef and Bénichou [8] and Liu et al [9] have recently validated the use of FDS in assessing the performance of emergency ventilation and detection systems for tunnel applications by extensively comparing the predictions of FDS against field and laboratory experiments. The comparison studies showed that both numerical predictions of FDS and measurements were, in general, in good agreements. The comparisons were conducted, at both near and far field of fire location, for several parameters including volumetric airflows, temperatures, and smoke optical densities (SODs).

Large fire HRR were not feasible for testing in the tunnel due to the risk of damage to the tunnel and its support systems. Therefore, a 30 MW gasoline pool fire (equivalent to a

bus or truck on fire) was used to conduct the numerical simulations for fires located at the tunnel centerline at CH 28+31 and 36+53 as listed in Table 4. This fire represents a typical design fire HRR recommended for roadway tunnels that do not carry dangerous hazardous goods [2]. In total, seven CFD simulations were conducted. As shown in Figure 7, the first four fire scenarios (CH28SCA, CH28SCB, CH28SCC, and CH28SCD) were simulated to represent a fire in the straight region of the tunnel at CH 28+31. To investigate the effect of the wall curvature of Tube C on the smoke movement, the other three scenarios (CH36SCA, CH36SCB and CH36SCC) were simulated to represent a fire in the curved region of the tunnel at CH 36+53.

The results and observations of the field fire tests for a fire HRR of 1 MW indicated that both ventilation scenarios CH28SCA and CH28SCB resulted in a limited backlayering distance. Therefore, it was decided to investigate the effect of a larger fire HRR (30 MW) on the performance of these ventilation scenarios. In addition, two possible ventilation schemes (CH28SCC & CH28SCD) were explored to determine their performance for a 30 MW fire in the straight portion of the tunnel section. Both CH28SCC and CH28SCD utilized the ceiling fans CF3, CF4, and CF5 in the supply mode. These fans were equipped with a number of saccardo nozzles (Figure 6).

All CFD simulations were carried out in the absence of traffic in the tunnel section. Normally, the traffic downstream of the fire would be cleared shortly after the fire initiation. Thus, the postulation of no traffic in the tunnel may not affect the outcome of the CFD simulations with regards to smoke movement and control downstream of the fire. However, the existence of traffic upstream of the fire would act as obstacles that can affect the movement of airflow.

Both the floor and ceiling of the modeled section of the tunnel have zero slopes. The actual geometry of Tube C has a curved portion in the range between CH 31+00 and CH 40+00 (Figure 1). Since FDS code handles only the physical domains as right parallelepipeds, *i.e.* boxes, the actual geometry of Tube C was slightly modified as shown in Figure 7. This modification was carried out using a process called “stair stepping” in which a series of rectangular obstructions are introduced to simulate the curved part of the domain. The stair stepping induces changes in the flow pattern near the wall by generating vortices at the sharp corners. These effects were minimized by smoothing out the jagged steps that made up the rectangular obstructions.

Grids or meshes were developed in which the volume within the tested section of the tunnel was divided into hundreds of thousands of control volumes or cells. In each cell, the governing equations (momentum, energy and diffusion equations) are solved as a function of time. The mesh was refined in the regions where large temporal and/or spatial gradients of key flow quantities were anticipated.

Ventilation vents were introduced to mimic the actual wall and ceiling vents in the tested section of the tunnel and in accordance with Figure 7. The number of vents for each fan and their location, and the operation mode of these fans are listed in Table 1. The fans volumetric flow rates and their mode of operations (exhaust or supply) for all ventilation

scenarios are listed in Table 4. Also, the resultant net flow due to the activated fans for each ventilation scenario is shown in this table. When the net flow was a positive value, this indicated that fresh air was drawn into the tunnel section at the portals and from other parts of the tunnel to balance the ventilation flow. Except for ventilation scenario CH28SCC in which there was airflow to the outside of the tunnel section, all ventilation scenarios drew fresh air from outside the modeled section. The field measurements revealed that fan CF2 did not function properly when it was operated in the supply mode. Therefore, a zero flow was assumed when this fan operated in the supply mode in ventilation scenarios CH28SCA and CH28SCC.

The modeled section of the tunnel extended from CH 17+00 to CH 45+00. In the numerical simulations, CH 17+00 and CH 45+00 are approximately taken at $X = 640$ m and $X \sim 0$ m, respectively. As shown in Figure 7, there are four portals of Tubes A, C, and D, namely:

- The west portal of Tube D with 2 lanes ($X = 0$ and $Y = 129 - 141$ m, $Z = 0 - 5$ m),
- The south portal of Tube C with 1 lane ($X = 26 - 31$ m, $Y = 0$ m and $Z = 0 - 5$ m),
- West portal of Tube A with 3 lanes ($X = 400$ m, $Y = 297 - 310$ m, $Z = 0 - 5$ m), and
- East portal of Tube A with 5 lanes ($X = 640$ m, $Y = 297 - 320$ m, $Z = 0 - 5$ m).

As indicated earlier, the field tests showed that the measured prevailing wind speed was about zero at all portals listed above. Hence, the wind speed at these portals was assumed to be zero in all simulations. Consequently, the boundary conditions at these portals were taken as open vents. In this case, the total pressure in the modeled section of the tunnel would be approximately equal to the atmospheric pressure. Therefore, the mass flow rate at each of these portals was calculated and its value differed from a ventilation scenario to another, depending on the amount of mass flow rate entering or exiting the modeled section of the tunnel from each activated fan.

All seven numerical simulations listed in Table 4 were conducted for a duration time of 900 s. In all numerical simulations, both the fire and ventilation system were simultaneously activated at time equal zero. Also, the HRR of the fire and the values of the flow rates produced by the activated fans were linearly ramped from zero to their full values during the first second of the simulation time. In an actual fire incident, however, the ventilation system would be activated after a certain period of time after the fire initiation, which depends on how fast the tunnel operator take the action in activating the ventilation system.

The study focused mainly on the roadway of the tunnel and not on the egress routes. Within the scope of this study, both temperature and visibility were selected to judge the efficiency of different ventilation strategies.

Characteristics of the Gasoline Pool Fire Used in the CFD Simulation

In all simulations, a 30 MW gasoline pool fire was considered. As indicated earlier, this fire HRR (a bus or truck on fire) represents a rational design fire [2]. It was assumed that the gasoline fuel ($C_{16}H_{34}$) is being burned with constant yields of CO and Soot according to:

In FDS version 4, it was assumed that the CO and Soot are created at the flame and transported with the combustion products with no growth, oxidation or after burning. For simulated fuel, the values of the yields of CO and Soot were taken as 0.131 and 0.360, respectively [5]. Based on these yield values, the actual stoichiometric coefficients in Eq. (3) are: $\nu_{O_2} = 17.191$, $\nu_{CO_2} = 8.163$, $\nu_{H_2O} = 17.0$, $\nu_{CO} = 1.057$ and $\nu_{Soot} = 6.780$.

As shown in Figure 8, the 30 MW gasoline pool fire was represented by a 3.2 x 2.5 x 1.5 m parallelepiped made of Steel and located at the centerline of the tunnel. The top surface of the parallelepiped with an area of 8.0 m² subjected to a heat release rate per unit area (HRRPUA) equal to 3,750 kW/m², which corresponds to fire of a HRR of 30 MW. The results of the CFD simulations are presented and discussed next. These results include the following:

- Smoke propagation within the period of simulation (900 s).
- Temperatures and visibilities at different elevations at the tunnel centerline.
- Average temperatures and visibilities at the tunnel centerline. For a given location along the tunnel, the average temperature and visibility corresponded to their mean values at different elevations at the tunnel centerline.

The results from these simulations showed that scenarios CH28SCC and CH28SCD for a fire at CH 28+31, and scenario CH36SCC for fire at CH 36+53 produced the best ventilation performance. In the next section, the airflow, smoke propagation, visibility and temperature distributions in the tunnel section are discussed in detail for CH28SCC and CH36SCC. Additionally, the results of other ventilation scenarios are briefly summarized.

RESULTS AND DISCUSSIONS

Figure 9 shows sample results of the temporal change of the mass flow rate at different cross-sections along the tunnel for CH28SCC. The steady state conditions were achieved at all locations after approximately 200 s. This was typical for all simulations. As shown in Figure 9, because the flow regime in the tunnel was quite turbulent, the instantaneous mass flow rate (dashed lines) oscillated irregularly with time. The time-smoothed mass flow rate (solid lines) was obtained by taking a time average of the mass flow rate over a time interval of ~10 s. In all scenarios, the magnitude of the turbulent disturbance (i.e. intensity of turbulence, which is the ratio of time average of the square values of the mass flow rate fluctuations to its time average) had values < 10%.

Airflow Profiles

Figure 10 shows the volumetric flow rate at different cross-sections of the tunnel section at the end of simulation (900 s) for a fire at CH 28+31. For CH28SCC, the ceiling fans CF1, CF3, CF4 and CF5 were activated in the supply mode, while the wall fans WF1, WF2, and WF3 were activated in the exhaust mode (Table 4). Scenario CH28SCD was

similar to CH28SCC except that the ceiling fan CF1 was not activated in CH28SCD. The activation of ceiling fan CF1 in scenario CH28SCC resulted in a higher negative airflow upstream and in the vicinity of the fire than that in CH28SCD. Among the four ventilation scenarios, CH28SCC resulted in the highest negative airflow (airflow in the same direction of traffic), which in turn resulted in the shortest backlayering length and the best visibility upstream of the fire.

In ventilation scenario CH36SCA for a fire at CH 36+53, both the lateral vents and tunnel horizontal curvature induced turbulence that inhibited strong longitudinal airflow in the curved portion of the tunnel section. This was confirmed in the in-situ test observations where, the induced turbulence cooled down the hot buoyant smoke layer and enhanced its dilution (Figure 11). Scenario CH36SCC was similar to CH36SCB except that the ceiling fans CF3, CF4, CF5 (operated in supply mode) and the wall fans WF2 and WF3 (operated in exhaust mode) were activated for CH36SCC and were not activated for CH36SCB. As shown in Figure 12 for CH36SCC, activating the wall fans WF2 and WF3, which had a considerable volumetric flow rate in the exhaust mode ($85 \text{ m}^3/\text{s}$) increased the negative airflow upstream of the fire. Also, activating ceiling fans CF3, CF4 and CF5 in the supply mode induced a jet-like airflow conditions (see Figure 13), resulting an increase in the negative airflow upstream of the fire, hence causing a shorter backlayering length upstream of the fire.

Smoke Propagations

Figure 14 shows the smoke propagations for scenario CH28SCC. Both CH28SCC and CH28SCD resulted in fresh air being drawn from the west portal of Tube A (CH 25+00) into Tube C causing a delay in backlayering in Tube C. Activating wall fans WF2 and WF3 in the exhaust mode in the four scenarios for a fire at CH 28+31 resulted in not only creating a positive airflow downstream of the fire (Figure 10) but also extracting the smoke from downstream of the fire. The higher the positive airflow downstream of the fire the more confined was the smoke front. Moreover, the activation of ceiling fan CF1 in the supply mode resulted in a slightly lower positive airflow in CH28SCC than that in CH28SCD downstream of the fire. In 900 s, the smoke front traveled a distance of 395 m downstream of fire for CH28SCC (Figure 14d) versus a distance of 364 m for CH28SCD. In both scenarios, the length of backlayering upstream of the fire was 86 m.

The CFD results showed that in 41 s and 684 s after ignition for scenario CH28SCA, the backlayering length increased from 51 m and 153 m (entrance of Tube C), respectively. In the period from 684 s until the end of simulation (900 s), the smoke front upstream of the fire did not move beyond the entrance of Tube C. In 50 s in scenario CH28SCB, the backlayering length upstream of the fire was 61 m. The smoke front in scenario CH28SCB reached the entrance of Tube C (153 m upstream of the fire) in 347 s compared to 684 s in CH28SCA. In the period from 347 s to 900 s for scenario CH28SCB, the backlayering extent did not change.

Both scenarios CH28SCC and CH28SCCD produced the shortest backlayering length upstream of the fire (86 m) among the simulated scenarios for a fire at CH 28+31 (located in the straight region of Tube C). However, CH28SCD was the most successful scenario

in confining the smoke front downstream of the fire with a short backlayering length upstream of the fire (86 m).

Figure 15 shows the smoke propagations in scenario CH36SCC for a fire at CH 36+53. As shown in this figure, the smoke front reached the west portal of Tube D after 95 s from initiating the fire (Figure 15b). At 95 s, the backlayering reached CH 31+30 (159 m upstream of the fire); and 18 s later (at 113 s), this backlayering moved 16 m further and reached the beginning of the curved region of Tube C (at CH 30+80, 175 m upstream of the fire). At 900 s (end of simulation), the smoke front reached CH 42+25 (174 m downstream of the fire) in scenarios CH36SCB and CH36SCC. However, at this time (900 s), the backlayering in CH36SCC reached CH 29+93 (201 m upstream of the fire, see Figure 15d) compared to 241 m upstream of the fire in CH36SCB. Moreover, the CFD results for CH36SCA showed that activating the wall fan WF4 in the supply mode, diluted the smoke to a lower concentration, but caused the diluted smoke to fill the entire section of the tunnel upstream of the fire. This phenomenon was also confirmed in the in-situ fire tests.

A close examination for the CFD results of scenario CH36SCA showed that the backlayering upstream of the fire reached the east portal of Tube A after 522 s. For CH36SCB and in 81 s, the backlayering reached CH 32+81 (113 m upstream of the fire); and 95 s later (at 176 s), the backlayering moved 62 m further and reached the beginning of the curved region of Tube C (at CH 30+80, 175 m upstream of the fire). In the period from 176 s – 900 s, the backlayering reached CH 28+63 (241 m upstream of the fire). In summary, in terms of smoke movement in both upstream and downstream of the fire, CH36SCC was the best scenario among the simulated scenarios for a fire at CH 36+53 (located in the curved region of Tube C).

Visibility Profiles

Figure 16 and Figure 17 compare the average visibilities at the centerline of the tunnel for the different ventilation scenarios for a fire at CH 28+31 and CH 36+53, respectively, at the end of simulation time (900 s). The average visibility shown in these figures is the mean value of the visibilities at elevations 0.1, 0.9, 1.9, 2.9, 3.9 and 4.9 m at the centerline of the tunnel. The visibility (VIS in m), was calculated in FDS version 4 as follows [6]:

$$VIS = C/K, \text{ and } K = K_m(\rho Y_s) \quad (\text{Eq. 4})$$

where:

K = light extinction coefficient (m^{-1})

K_m = mass specific extinction coefficient ($7,600 \text{ m}^2/\text{kg}$ [6])

ρY_s = density of smoke particulate (kg/m^3), which varies from point to point in the computational domain, and

C = dimensionless proportionality constant, which equal to 3 for light-reflecting sign and building components in reflected light [6].

Figure 16 shows the average visibility for the four scenarios for a fire at CH 28+31. Activating ceiling fans CF1 and CF2 in the exhaust mode in CH28SCB drew the smoke from the vicinity of the fire towards the upstream of the fire, resulting in the best visibility conditions downstream of the fire and in the vicinity of the fire, and the worst visibility conditions upstream of the fire. Having a good visibility in the vicinity of the fire as in CH28SCB is desirable for fire fighters. On the other hand, a good visibility in the vicinity of the fire indicated high oxygen concentration that is available to sustain the combustion at a high rate, resulting in higher temperatures in the vicinity of fire.

When the ceiling fan CF1 was activated in supply mode in scenario CH28SCA, the fresh air from this fan opposed the movement of the smoke upstream of the fire, resulting in higher visibility upstream of the fire and lower visibility downstream of the fire compared to that in scenarios CH28SCB (Figure 16). Activating the ceiling fans CF3, CF4 and CF5 in supply mode in scenarios CH28SCC and CH28SCD (Table 4) resulted in a much better visibility upstream of the fire compared to that in scenarios CH28SCA and CH28SCB. Also, activating these fans caused lower visibility downstream of the fire in scenarios CH28SCC and CH28SCD compared to scenarios CH28SCA and CH28SCB (Figure 16).

Unlike the fire located at CH 28+31 (in the straight region), there was poor visibility at the fire location in the three ventilation scenarios with the fire located at CH 36+53 (in the curved region, Figure 17). Placing a fire in the curved region, however, caused a better mixing between the fresh air and the combustion products (due to the turbulence enhancement caused by the curved wall) than when the fire was located in the straight region, resulting in: (a) poor visibility in the vicinity of the fire, hence lower the oxygen concentration and consequently lower combustion rate, and (b) a lower the peak temperature as will be shown next.

As shown in Figure 17, the visibilities downstream of the fire for the three ventilation scenarios were similar. However, CH36SCC produced the best visibility upstream of the fire. For example, at CH 30+14 (195 m upstream of the fire), the average visibility in scenario CH36SCC was 12 m compared to about 0 m in CH36SCB and CH36SCA. Figure 17 showed that the shortest backlayering and the best visibility upstream of the fire were in scenario CH36SCC.

Temperature Profiles

The average temperatures at the tunnel centerline for ventilation scenarios for fires at CH 28+31 (CH28SCA, CH28SCB, CH28SCC and CH28SCD), and CH 36+53 (CH36SCA, CH36SCB, and CH36SCC) are shown in Figure 18 and Figure 19, respectively. It should be noted that the average temperature at each location along the centerline of the tunnel was the mean values of the temperatures at all elevations at the tunnel centerline. For a fire at CH 28+31, CH28SCB had the highest average temperature (469°C) at the fire location, while simulation CH28SCD had the lowest average temperature (251°C). As a result of activating the ceiling fans CF3, CF4 and CF5 in supply mode in CH28SCC and CH28SCD, the average temperatures downstream of the fire in these simulations were higher than that in simulations CH28SCA and CH28SCB (Figure 18). While, the

average temperatures upstream of the fire in simulations CH28SCA and CH28SCB were higher than that in CH28SCC and CH28SCD.

For a fire at CH 36+53, Figure 19 shows that at the fire location, scenario CH36SCC resulted in the highest average temperature (323°C), while the other two simulations CH36SCA and CH36SCB produced a lower average temperature (~277°C). The average temperature downstream of the fire in scenario CH36SCA was slightly higher than that in scenarios CH36SCB and CH36SCC. Additionally, the average temperatures upstream of the fire in simulations CH28SCB and CH28SCC were approximately the same, and higher than that in simulation CH36SCA for a distance from the fire < ~160 m. For distance from the fire > ~160 m, the average temperatures in scenarios CH28SCB and CH28SCC were lower than that in scenario CH36SCA.

Table 5 summarized the CFD results for the seven ventilation scenarios for fires at CH28+31 and CH36+53. The CFD results showed that when the fire was located in the curved region of Tube C, it was observed that a good mixing between the fresh air and the combustion products took place due to the effect of wall curvature. This mixing process resulted in reducing the highest peak and highest average temperatures and increasing the extent of backlayering phenomenon. Consequently, having a fire accident in the curved region, the trapped vehicles upstream of the fire would receive a lower amount of heat by radiation than if the accident occurred in the straight region of Tube C. On the other hand, a fire accident in the curved region is more serious than that in the straight region in terms of smoke inhalation and visibility.

SUMMARY AND CONCLUSIONS

Seven numerical transient CFD simulations were carried out to investigate the effectiveness of the in-place ventilation strategies for removing smoke and hot gases produced by fires in the tested section of the tunnel. For these applications, it has been shown that FDS is a good tool to be used for predicting volumetric airflows, temperatures, and smoke optical densities. This tool was used in this study to conduct numerical simulations for a fire HRR of 30 MW under different ventilation scenarios for two fire locations in the tested section of the tunnel. The experimental part of this study provided the necessary initial and boundary conditions for the numerical simulations. The first four fire scenarios were simulated for a fire in the straight region of the tunnel section. To investigate the effect of the wall curvature of Tube C on ventilation performance, another three fire scenarios were simulated for the same fire HRR of 30 MW. The results of these scenarios are summarized in Table 5.

Based on the field fire tests and the CFD simulations, it was observed that:

- For a fire located in the straight part, scenario CH28SCD limited the extent of backlayering and delayed its the occurrence. This scenario produced the shortest backlayering distance (86 m). Moreover, this scenario produced the lowest peak temperature. The activation of the ceiling fans CF3, CF4, and CF5 has induced a

- jet-like airflow conditions upstream of the fire limiting and controlling backlayering and reducing temperatures at the fire location.
- For a fire located in the curved part of Tube C at Chainage 36, the ventilation scenario CH36SCC produced the shortest backlayering distance (175 m).
 - Large size exhaust wall vents are more effective in removing smoke and fire products.
 - In the curved region of the tunnel, exhaust vents were distributed in both the north and south walls. This induced localized effect around these vents on both sides. The local effect not only reduced the efficiencies of the wall fans, but also formed a dead zone around the centerline with small longitudinal airflow. This also had been confirmed from fire tests at CH 36+00.
 - To minimize the smoke backlayering in the curved region, it is necessary to install ceiling jet fan(s) along the curved region (CH 32 + 00 to CH 40 + 00) to eliminate the dead zone and produce a proper longitudinal flow towards the west direction (i.e. in the direction of traffic flow).

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Table 1 Mode of operations and locations of the existed fans in the tested section of the tunnel (see Figure 1 and Figure 7)

Fan	Mode of Operation	Number of Vents	Location	CH
CF1	normal (exhaust) reverse (supply)	18 vents	ceiling	22+63
CF2	normal (exhaust) reverse (supply)	18 vents	ceiling	22+86
CF3	normal (supply)	24 saccardo nozzles	ceiling	17+17 – 17+85
CF4	normal (supply)	24 saccardo nozzles	ceiling	17+17 – 17+85
CF5	normal (supply)	24 saccardo nozzles	ceiling	17+17 – 17+85
WF1	reverse (exhaust)	52 vents	south wall	24+16 – 29+34
WF2	normal (exhaust)	1 vent	south wall	30+06
WF3	normal (exhaust)	1 vent	south wall	30+36
WF4	normal (supply)	27 vents	south wall	31+00 – 37+10
	reverse (exhaust)	23 vents	north wall	
WF5	reverse (exhaust)	10 vents	north wall	37+44 – 38+20
WF6	reverse (exhaust)	36 vents	south wall	37+44 – 41+54
WF7	normal (exhaust)	1 vent	north wall	41+80
WF8	normal (exhaust)	1 vent	north wall	41+60
WF9	normal (exhaust)	1 vent	south wall	42+00

Table 2 Locations of temperature and Smoke Optical Density (SOD) measurements

Test	Drops	Location (CH)	Distance from Fire [#] (m)
CH28SCA CH28SCB	Drop 1	28 + 55	+1.5
	Fire	28 + 50	0.0
	Drop 2	30 + 00	+45.7
	Drop 3	31 + 50	+91.4
	Drop 4	27 + 00	-45.7
CH36SCA CH36SCB	Drop 1	36 + 00	0.0
	Fire	36 + 00	0.0
	Drop 2	37 + 75	+53.3
	Drop 3	39 + 25	+99.1
	Drop 4	34 + 25	-53.3

[#] Positive values are for downstream of fire

Table 3 Activated ventilation scenarios used in during the in-situ fire tests for 1 MW fire at CH 28 + 50 and CH 36 + 00

Ventilation Scenario	Fan	Mode of Operation	Total mass flow rate (kg/s)
CH28SCA	CF1	Supply	-64.38
	CF2	Supply	0.0
	WF1	Exhaust	26.48
	WF2, WF3	Exhaust	102.51
Net	64.61		
CH28SCB	CF1	Exhaust	107.29
	CF2	Exhaust	80.47
	WF1	Exhaust	26.48
	WF2, WF3	Exhaust	102.51
Net	316.75		
CH36SCA	WF4	Supply	-66.01
	WF6	Exhaust	31.08
	WF7	Exhaust	31.52
	WF8	Exhaust	51.80
	WF5	Exhaust	38.70
	WF9	Exhaust	64.45
Net	151.54		
CH36SCB	WF4	Exhaust	39.60
	WF6	Exhaust	31.08
	WF7	Exhaust	31.52
	WF8	Exhaust	51.80
	WF9	Exhaust	64.45
	WF5	Exhaust	38.70
Net	257.15		

Table 4 Activated ventilation scenarios used in the numerical simulation for 30 MW fire at CH 28 + 31 and CH 36 + 53

Ventilation Scenario	Fan	Mode of Operation	Total mass flow rate (kg/s)
CH28SCA	CF1	Supply	-64.38
	CF2	Supply	0.0
	WF1	Exhaust	26.48
	WF2, WF3	Exhaust	102.51
Net	64.61		
CH28SCB	CF1	Exhaust	107.29
	CF2	Exhaust	80.47
	WF1	Exhaust	26.48
	WF2, WF3	Exhaust	102.51
Net	316.75		
CH28SCC	CF1	Supply	-64.38
	CF2	Supply	0.0
	WF1	Exhaust	26.48
	WF2, WF3	Exhaust	102.51
	CF3, CF4, CF5	Supply	-112.84
Net	-48.23		
CH28SCD	WF1	Exhaust	26.48
	WF2, WF3	Exhaust	102.51
	CF3, CF4, CF5	Supply	-112.84
Net	16.14		
CH36SCA	WF4	Supply	-66.01
	WF6	Exhaust	31.08
	WF7	Exhaust	31.52
	WF8	Exhaust	51.80
	WF5	Exhaust	38.70
Net	87.09		
CH36SCB	WF4	Exhaust	39.60
	WF6	Exhaust	31.08
	WF7	Exhaust	31.52
	WF8	Exhaust	51.80
	WF10	Exhaust	31.51
	WF5	Exhaust	38.70
Net	224.21		
CH36SCC	WF4	Exhaust	39.60
	WF6	Exhaust	31.08
	WF7	Exhaust	31.52
	WF8	Exhaust	51.80
	WF10	Exhaust	31.51
	WF5	Exhaust	38.70
	CF3, CF4, CF5	Supply	-112.84
	WF2, WF3	Exhaust	102.51
Net	213.88		

Table 5 Summary of the simulation results for all ventilation scenario studied

Fire Scenario	Backlayering		Time s (min) [*]	Visibility (m) ^{**}	Maximum Temperatures (°C)	
	Region (CH)	Length (m)			Average	Peak
For fire in the straight section of Tube C of a HRR of 30 MW or less						
CH28SCA	23+30 & 28+31	153	684 (11.5)	5	486	1110
CH28SCB	23+30 & 28+31	153	347 (6)	2-3	534	1160
CH28SCC ^{\$}	25+50 & 28+31	86	567 (9.5)	< 2	286	667
CH28SCD ^{\$}	25+50 & 28+31	86	734 (12)	< 1	303	662
For fire in the curved section of Tube C of a HRR of 30 MW or less						
CH36SCA	17+00 & 36+53	595	900 (15)	< 1	276	831
CH36SCB	28+63 & 36+53	241	900 (15)	0 – 7	277	773
CH36SCC ^{\$}	30+80 & 36+53	175	113 (2)	2.5	323	843

^{*} Time from ignition until maximum backlayering distance

^{**} Average visibility within the backlayering region

^{\$} Favorable ventilation scenario

Figure 1 A schematic of the investigated section of the tunnel

(a) Ventilation scenarios in straight part resulted in backlayering

(b) Ventilation scenarios in curved part caused a zero airflow (vertical plume)

(c) SOD values in curved part were significantly higher

(d) Large size exhaust wall vents were more effective in removing smoke

Figure 2 Field fire tests observations

Figure 3 Measurements of maximum ceiling temperature at Drop 1

Figure 4 Measurements of the maximum vertical temperature profiles

Figure 5 Measurements of maximum SOD profiles

Figure 6 Saccardo nozzles of fans CF3, CF4, and CF5

Figure 7 A schematic of the approximated geometry of modeled section of the tunnel

Figure 8 A schematic for the 30 MW Gasoline pool fire.

Figure 9 Temporal change of the mass flow at different cross-sections of the tunnel in CH28SCC

Figure 10 volumetric flow rates at different tunnel cross-sections for 30 MW fires at CH 28+31

Figure 11 Vector plot of airflow speeds at the fire location – CH36SCA

Figure 12 Volumetric flow rate at different tunnel cross-sections for fire at CH 36+53

Figure 13 Contour and vector plots of airflow speed close to ceiling vents of fans CF3, CF4, and CF5

Figure 14 Smoke propagation for fire at CH 28+31 for CH28SCC

Figure 15 Smoke propagation for fire at CH 36+53 for scenario CH36SCC

Figure 16 Average visibilities along the height at centerline of the tunnel for fire at CH 28+31

Figure 17 Average visibilities along the height at centerline of the tunnel for fire at CH 36+53

Figure 18 Average temperatures along the height at centerline of the tunnel for fire at CH 28+31

Figure 19 Average temperatures along the height at centerline of the tunnel for fire at CH 36+53