Fire and smoke management in a uni-directional road tunnel for a congested traffic condition

Y Liu, J Munro
Parsons Brinckerhoff Australia
B Dandie
Thiess Pty Ltd., Australia

ABSTRACT

Emergency smoke ventilation for a uni-directional traffic road tunnel is studied using a CFD modelling approach. Fire scenarios in an uphill ramp for congested traffic conditions have been considered. Based on a longitudinal smoke ventilation system with a damper smoke-extraction device on the ceiling soffit, the impact of longitudinal ventilation (LV) control, operation of fire suppression intervention and emergency response delay have been quantitatively investigated.

An assessment conducted with CFD modelling quantitatively shows to what extent the visibility is influenced. It has been revealed that airflow velocities can influence the performance of damper smoke-extraction. Different longitudinal airflow velocity should be maintained for fires in different tunnel locations under congested traffic conditions. This is important for tunnels with a fire suppression system, as smoke flows to the lower location when hot layer stratification is disturbed by the application of water. Fire suppression can cool down the smoke temperature significantly, but the visibility in the downstream portion of the tunnel can be impacted if longitudinal ventilation is not properly controlled.

For the modelled conditions with a heavy goods vehicle (HGV) fire in a 5% uphill ramp section of a tunnel, an LV flow velocity of 2m/s can maintain tenable conditions downstream for congested traffic conditions.

Key words: fire emergency, longitudinal ventilation, smoke extraction, road tunnel

ABBREVIATIONS

ASET – available safe evacuation time
CCTV – Closed Circuit Television
CFD – computational fluid dynamics
FS – fire scenario
HGV – heavy goods vehicle
HRR – heat release rate
LV – longitudinal ventilation
MW – Mega Watts
NIST – National Institute of Standard and Technology, USA
OG – occupants group
RSET – required safe evacuation time
1 INTRODUCTION

Smoke generated in a road tunnel as a result of an accident fire can pose a risk to occupants in the tunnel if not properly managed. The 1999 Mont Blanc tunnel fire, which killed 39 people, is an example of such an event \(^1\). For tunnel designers and operators, the most important issue to consider is the protection of the lives of the tunnel occupants (NFPA502, 2004) \(^2\).

To assist a tunnel fire emergency response system, careful consideration of the smoke management system and strategy is essential. This system should have the capabilities to respond to different fire scenarios.

As in any fire and life safety engineering systems, a tunnel emergency response can consist of measures such as the emergency ventilation system to manage the smoke, egress routes to evacuate the occupants to a safe place, fire suppression system to control the fire, fire resistant construction to prevent tunnel collapse, and a fire and incident response management system to coordinate the response \(^3\). A good design is one that can operate and coordinate all of the above systems effectively without complexity.

In a fire incident, it is well known that the major parameters that affect smoke spread and its stratification in a tunnel are the air flow, fire size, the presence of air, fire suppression and the tunnel geometry. A typical fire incident involves a sequence of events: fire initiation, fire growth, activation of fire emergency response system, self evacuation and assisted evacuation of the occupants by the emergency services \(^4\). Prior to the activation of emergency procedures and emergency equipment, the fire needs to be detected and confirmed first.

In this paper a quantitative assessment considering the impact of longitudinal ventilation control, fire suppression, emergency response time, traffic condition and road gradient is undertaken to examine the performance of the fire safety and smoke management system. The objective is to provide insight to the extent that these parameters may influence the tenability of the tunnel.

Fire may occur anywhere in a traffic tunnel. For a tunnel with sections of varied gradients — uphill, downhill or no gradient — different management strategies are required for different traffic conditions. Table 1 lists the different fire scenarios and the requirements to avoid smoke migration for two different traffic conditions and three different road gradients. As will be explained in the following sections, the worst-case scenario for normal free-flowing traffic conditions is for a fire to occur in a downhill section of the tunnel; whereas the worst-case scenario for congested traffic conditions is for a fire in an uphill section. Congested traffic for the purpose of this paper is defined as traffic moving at a rate that occupants can be impacted by the fire-generated smoke.

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>traffic</th>
<th>Tunnel grad</th>
<th>Avoid smoke migration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Non-congested</td>
<td>Down hill</td>
<td>upstream</td>
</tr>
<tr>
<td>B</td>
<td>Non-congested</td>
<td>0%</td>
<td>upstream</td>
</tr>
<tr>
<td>C</td>
<td>Non-congested</td>
<td>Uphill</td>
<td>upstream</td>
</tr>
<tr>
<td>D</td>
<td>Congested</td>
<td>Down hill</td>
<td>Upstream &amp; downstream</td>
</tr>
<tr>
<td>E</td>
<td>Congested</td>
<td>0%</td>
<td>Upstream &amp; downstream</td>
</tr>
<tr>
<td>F</td>
<td>Congested</td>
<td>Uphill</td>
<td>Upstream &amp; downstream</td>
</tr>
</tbody>
</table>

Table 1: Fire scenarios under different traffic conditions
Under free-flowing traffic conditions without traffic congestion, as in scenarios A, B and C, downstream smoke migration does not need to be considered because downstream vehicles can easily drive away and out of the tunnel. Under normal traffic conditions the worst-case scenario is for a fire to occur in a downhill ramp. In a downhill ramp, smoke may travel upstream due to buoyancy flow. Under this scenario, fire and life safety requirements are achieved by maintaining an airflow that is larger than the critical velocity, which is the minimum velocity to prevent smoke backlayering upstream.

Under congested traffic conditions, however, as in scenarios D, E and F, both upstream and downstream of the fire should avoid smoke migration to keep conditions tenable for the occupants. Tenability has been studied extensively by other investigators with well-researched critical velocities to prevent smoke backlayering in the upstream\textsuperscript{[5-10]}. As such, the investigation of tenability is not repeated in the present paper. Downstream under congested traffic condition, the worst-case scenario is for a fire to occur in an uphill ramp. In an uphill ramp, occupants in the downstream section may become vulnerable when both the longitudinal ventilation airflow and the fire generated buoyancy flow drive the smoke uphill towards the occupants in the downstream section. This paper focuses mainly on smoke control strategies to maintain the control of smoke downstream of the fire for the uphill section of a tunnel under congested traffic conditions.

One solution that is considered in tunnel safety designs is the use of localised smoke extraction above and near the fire. The system considered for this paper consists of a large exhaust duct placed at the ceiling and smoke intake openings at regular intervals in the system. The openings are regulated by remote-control dampers. In the event of a fire, two dampers near the fire, one in the upstream and one in the downstream, are opened to capture the fire generated smoke into the smoke duct above of the main traffic tunnel. With the opening of the two smoke extraction dampers, smoke is contained within the section between the two damper extraction points.

Fire suppression intervention is known to disturb the smoke layer stratification, causing the smoke layer to move to a lower level. Quantitative assessment is required to show to what degree the smoke is influenced, when the longitudinal airflow pushes lower-level smoke downstream well beyond the damper extraction point.

In the present study, computational fluid dynamics (CFD) is used to quantitatively study the impact on fire life safety of different smoke management strategies for an uphill tunnel section with congested traffic conditions. The emphasis is to study the impact of upstream airflow control and the influence of the activation of the ventilation system.

2 FIRE AND SMOKE MANAGEMENT STRATEGIES

In this study, the tunnel section is assumed to be a uni-directional 2-lane road tunnel with a 5% uphill gradient in the direction of the traffic and the longitudinal ventilation. The tunnel is assumed to be 9m wide by 6.4m high. Figure 1 and Figure 2 show the cross-section and the side view of the 2-lane tunnel with congested traffic, respectively.

The smoke extraction is designed with localised remotely controlled dampers every 60m along the tunnel in the ceiling. The purpose is to contain the smoke within a 60 m long smoke zone between two smoke extraction points, as shown in Figure 2. These dampers only open in case of fire.
A design fire of 50 MW with a soot production rate of 10% is assumed for scenarios with and without fire suppression. This fire represents a heavy goods vehicle (HGV) fire. The assumption for the 50MW fire includes a reduction of fire HRR for scenarios with fire suppression, this is based on the assumption that the fire is not fully controlled as the seat of the fire is usually inside the vehicle, and therefore is shielded from the deluge water applied from the tunnel ceiling. Fire suppression effects include cooling of the fire generated smoke and the suppression of fire growth to avoid fire spreading to other vehicles. The design fire growth curve and a reference ultra-fast fire curve are plotted in Figure 3. The design fire is assumed to reach a heat release rate (HRR) of 2 MW at 3 minute and then the maximum HRR at 6 minute. The design fire is conservatively assumed to have a growth rate faster than that of the ultra-fast fire.
Under normal free-flowing traffic conditions, vehicles are assumed to travel at a speed of 80 km/hr, which can generate longitudinal ventilation (LV) airflow because of the piston effects. However, traffic congestion may occasionally occur. When the traffic flow drops, the LV airflow is maintained by jet fans to dilute pollutants. Upon the detection and confirmation of a fire incident, emergency procedures are initiated and a series of actions are taken, including the switch from normal ventilation mode to emergency ventilation mode, activation of the smoke extraction dampers near the fire site, and operation of the suppression system, etc. Assumed time sequences of some critical actions are summarized in Table 2.

In this study, the tunnel ventilation is assumed to begin operating in a fire mode at 3 minute since fire initiation. This is to allow for detection of the fire incident and to account for the response time of the system. In a sensitivity assessment to quantify the impact of an action response delay, a five minute response time is assumed.

### Table 2: Key emergency actions

<table>
<thead>
<tr>
<th>Item #</th>
<th>Action</th>
<th>Response delay [minutes]</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CCTV</td>
<td>1</td>
<td>Fire detection</td>
</tr>
<tr>
<td>2</td>
<td>Live broadcast</td>
<td>2</td>
<td>Warning of evacuation</td>
</tr>
<tr>
<td>3</td>
<td>Longitudinal ventilation control</td>
<td>3 ~ 5</td>
<td>Enhance smoke capture</td>
</tr>
<tr>
<td>4</td>
<td>Exhaust dampers open</td>
<td>3 ~ 5</td>
<td>Smoke extraction</td>
</tr>
<tr>
<td>5</td>
<td>Water discharges from nozzles</td>
<td>3</td>
<td>Fire suppression (if applicable)</td>
</tr>
</tbody>
</table>

In this example in the event of a fire incident, the fire is assumed to be detected via the tunnel fire detection system within 1 minute, and the live broadcast system is able to announce the evacuation within 2 minute. Fire suppression nozzles covering a 90 m section above the fire, as shown in Figure 2, is assumed to be activated to control the fire within 3 minute. The 90-m section consists of three 30 m deluge zones with the fire located in the centre of the deluge zone. A water application rate of 10mm/min for the entire 90 m section, delivering 120L/min in each nozzle, is assumed. The nozzles are assumed spaced 3m x 4m below the tunnel ceiling, as shown in Figure 4.

Water discharge distribution to achieve 10 mm/min per m² for a deluge fire suppression system, symbol ♦ refers to a nozzle

![Figure 4: Plan of deluge water discharge nozzle](image-url)
The smoke exhaust rate needs to include a control of the upstream longitudinal airflow velocity to prevent backlayering flow supplemented by jet fans as required. This smoke exhaust should also have the capability to generate sufficient reverse flow in the downstream to prevent smoke flow past the downstream extraction damper.

3 COMPUTER MODELLING AND ASSUMPTIONS

The Fire Dynamic Simulator (FDS) \[11\] is a computational fluid dynamics (CFD) package developed by the National Institute of Standards and Technology (NIST) in the USA for modelling fire growth and smoke transport. This software package, a popular tool that is often employed by the fire engineering community \[12-14\], is used in this study. The computational domain is 240m long x 9m wide x 6.4m high. The number of mesh in three coordinate directions is 480 x 45 x 32, which gives a total number of cells of 691,200. Only vehicular tunnel area is included in the modelling; smoke flow in the exhaust duct above the tunnel is not included in the modelling, but smoke extraction using dampers is specified on the ceiling of the vehicular tunnel. Open boundary condition is specified at each end of the tunnel. Computational time for each scenario is about 50 hours using a PC with a Pentium 2GHz processor.

At each extraction point, two dampers are assumed as shown in Figure 1, with one damper above each lane. The effective extraction area of each damper is assumed to be 3.5m x 2m. This gives a total extract area of 14m² at each damper location, such as at damper 1 or damper 2 in Figure 2.

Smoke temperature at the damper entrance is generally high enough to require consideration of the smoke density change. Therefore, the damper smoke extraction rate used in this CFD modelling is based on the mass flow rate. The base LV was factored up by 33% to achieve the total extract rate.

Scenarios that have been considered are summarized in Table 3. The base extraction rate used in the modelling is calculated as follows:

\[
\text{Base extraction rate} \ [\text{kg/s}] = \text{longitudinal ventilation (LV)} \ [\text{m/s}] \times \text{tunnel cross section} \ [\text{m}^2] \times \text{ambient density} \ [\text{kg/m}^3]
\]

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Longitudinal ventilation [m/s]</th>
<th>With/without fire suppression</th>
<th>Ventilation response time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>3.0</td>
<td>without deluge</td>
<td>3</td>
</tr>
<tr>
<td>2a</td>
<td>2.0</td>
<td>without deluge</td>
<td>3</td>
</tr>
<tr>
<td>3a</td>
<td>2.0</td>
<td>without deluge</td>
<td>5</td>
</tr>
<tr>
<td>1b</td>
<td>3.0</td>
<td>with deluge</td>
<td>3</td>
</tr>
<tr>
<td>2b</td>
<td>2.0</td>
<td>with deluge</td>
<td>3</td>
</tr>
<tr>
<td>3b</td>
<td>2.0</td>
<td>with deluge</td>
<td>5</td>
</tr>
</tbody>
</table>

Assuming a longitudinal ventilation flow of 3m/s, a total mass extraction rate of 277 kg/s is required to generate an average reverse flow of 1m/s from downstream.
4 OCCUPANTS EVACUATION

Occupants egress through the non-incident tube which is connected to the incident tunnel with cross-passages spaced every 120m along the tunnel, as shown in Figure 5. In a fire incident, the non-incident tunnel is pressurized to avoid smoke flow from the incident tunnel. Some evacuation parameters are summarized in Table 4.

![Non-incident tunnel tube with cross-passages and in-accessible cross-passage](image)

OG 1: occupants group who are within 30 m of the fire site
OG 2: occupants group who are more than 30 m from the fire site

**Figure 5: Plan of the tunnel occupants groups and cross-passage emergency exits**

<table>
<thead>
<tr>
<th>Occupant group</th>
<th>Distance from fire [m]</th>
<th>Detection time [s]</th>
<th>Pre-movement time [s]</th>
<th>Maximum travel time [s]</th>
<th>Required Safe Evacuation Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>&lt; 30 m</td>
<td>15</td>
<td>15</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>Group 2</td>
<td>&gt; 30 m</td>
<td>120</td>
<td>30</td>
<td>90</td>
<td>240</td>
</tr>
</tbody>
</table>

As shown in Table 4, tunnel occupants are assumed to be divided into two groups, and each group has a different response time. Figure 5 shows the evacuation plan: Group 1 are occupants within 30m of the fire site, Group 2 are those who are more than 30m away from the fire site. These two groups of people have different response times in a fire incident. Group 1 occupants become aware of the incident through visual cues etc and can respond quickly as they are closer to the fire site, the sum of detection time and pre-movement time is assumed to be 30s. Group 2 occupants are fairly far from the fire, but still can perceive the fire by the alert from the tunnel management centre. The sum of detection time and pre-movement time is assumed to be 150s. Travel time depends on the travel speed and the travel distance to the exit. The worst scenario is a fire in the vicinity of an emergency exit, which is rendered inaccessible by the fire. In that case, occupants have to use other exits which are 120 m away. Assuming a travel speed of 1.0 m/s in this study, the maximum travel time is 120s for Group 1 occupants. The Required Safe Evacuation Time (RSET) is the sum of detection time, pre-movement time and travel time. RSET with a safety factor of 1.2 and the smoke zone is displayed later in Figure 7. The safety factor of 1.2 was chosen for illustrative purposes only.
5 FIRE AND LIFE SAFETY ASSESSMENT

For a fire scenario under congested traffic conditions ideally airflow towards the fire zone from both upstream and downstream should be generated by extracting sufficient smoke using the two opened extract dampers, as shown in Figure 2. Performance of the damper extraction rate is assessed by examining the visibility at 2.1m above the tunnel road surface at the tunnel section beyond the last opened damper extraction point. Figure 6 shows the CFD modelling result of visibility on the central plane at 10 minutes after the fire initiation for different scenarios.

<table>
<thead>
<tr>
<th>Damper 1</th>
<th>Damper 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m</td>
<td>45 m</td>
</tr>
<tr>
<td>Figure 6-1a: LV=3 m/s without fire suppression in FS 1a</td>
<td>Figure 6-1b: LV=3 m/s with fire suppression in FS 1b</td>
</tr>
<tr>
<td>Damper 1</td>
<td>Damper 2</td>
</tr>
<tr>
<td>-15 m</td>
<td>45 m</td>
</tr>
<tr>
<td>Figure 6-2a: LV=2 m/s without fire suppression in FS 2a</td>
<td>Figure 6-2b: LV=2 m/s with fire suppression in FS 2b</td>
</tr>
</tbody>
</table>

Visibility and temperature are recorded from the CFD runs every 5m along the tunnel longitudinal direction. The monitoring location is 2.1m above the road surface at the centreline of the tunnel. For this assessment, Available Safe Evacuation Time (ASET) is calculated based on the acceptance visibility criteria of 7m at 2.1m above the tunnel floor in accordance with PIARC [5]. It should be noted that this PARIc visibility criteria is only an indication of tenability, as tenability depends on other factors such as CO concentration [15], etc. The smoke zone, which shows when and where in the tunnel the visibility is decreased to 7m at 2.1m above the road surface, is given in Figure 7. Tenability regained curve in Figure 7 refers to the time when smoke is cleared again in specific tunnel locations because of the activation of fire systems. An overview of the assessment results for all the considered scenarios is given in Table 5.

The simulation time for each scenario is 10 minutes. The temperature of the smoke passing through each individual damper extraction point was calculated using the gas law based on the recorded volume flow rate and mass flow rate passing through the damper openings. The transient smoke temperature development at damper 1 and damper 2 are shown in Figure 8.
Figure 7-1a: ASET/RSET for FS 1a (without fire suppression, LV=3 m/s, 3 minutes action delay)

Figure 7-1b: ASET/RSET for FS 1b (with fire suppression, LV=3 m/s, 3 minutes action delay)

Figure 7-2a: ASET/RSET for FS 2a (without fire suppression, LV=2 m/s, 3 minutes action delay)

Figure 7-2b: ASET/RSET for FS 2b (with fire suppression, LV=2 m/s, 3 minutes action delay)

Figure 7-3a: ASET/RSET for FS 3a (without fire suppression, LV=2 m/s, 5 minutes action delay)

Figure 7-3b: ASET/RSET for FS 3b (with fire suppression, LV=2 m/s, 5 minutes action delay)

Figure 7: RSET and the smoke zone showing when and where visibility drops to 7m
Table 5: CFD results of average smoke temperatures at two damper extraction points and visibility conditions

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>LV control [m/s]</th>
<th>Deluge</th>
<th>Action delay time [s]</th>
<th>Damper 1 temperature [°C]</th>
<th>Damper 2 temperature [°C]</th>
<th>Visibility criteria satisfied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>3.0</td>
<td>N</td>
<td>3</td>
<td>75</td>
<td>180</td>
<td>Y</td>
</tr>
<tr>
<td>2a</td>
<td>2.0</td>
<td>N</td>
<td>3</td>
<td>95</td>
<td>140</td>
<td>Y</td>
</tr>
<tr>
<td>3a</td>
<td>2.0</td>
<td>N</td>
<td>3</td>
<td>95</td>
<td>140</td>
<td>N</td>
</tr>
<tr>
<td>1b</td>
<td>3.0</td>
<td>Y</td>
<td>3</td>
<td>40</td>
<td>88</td>
<td>N</td>
</tr>
<tr>
<td>2b</td>
<td>2.0</td>
<td>Y</td>
<td>3</td>
<td>65</td>
<td>65</td>
<td>Y</td>
</tr>
<tr>
<td>3b</td>
<td>2.0</td>
<td>Y</td>
<td>5</td>
<td>65</td>
<td>65</td>
<td>N</td>
</tr>
</tbody>
</table>

Figure 8-1a: Smoke temperature at extraction point damper 1 for FS 1a and FS 1b [LV=3 m/s]

Figure 8-1b: Smoke temperature at extraction point damper 1 for FS 2a and FS 2b [LV=2 m/s]

Figure 8-2a: Smoke temperature at extraction point damper 2 for FS 1a and FS 1b [LV=3 m/s]

Figure 8-2b: Smoke temperature at extraction point damper 2 for FS 2a and FS 2b [LV=2 m/s]

Figure 8: Smoke temperature at damper extraction points
5.1 Influence of upstream LV control

5.1.1 Fire scenarios 1a and 2a – without fire suppression

In the cases without fire suppression, Figure 6-1a shows the visibility for FS 1a with upstream LV of 3 m/s. The results show that smoke flows downstream well beyond the downstream damper. However, as shown in Figure 7-1a, the impact on the visibility is minimal since the stratification layer is intact and smoke resides in the higher location.

If the upstream LV is controlled at 2 m/s (FS 2a), smoke is contained within the 60 m long smoke zone between two damper extraction points, as shown in Figure 6-2a. No smoke is visualized elsewhere. As shown in Figure 7-2a, unlimited visibility is retained for upstream and downstream, except for the 10 m long fire incident zone. This is because the lower longitudinal flow of 2 m/s generates a reverse flow from the ambient downstream and improved damper smoke capture of the fire generated smoke.

In FS 1a where longitudinal ventilation flow is controlled at 3 m/s and without fire suppression, even though the fire is closer to the damper 1 in the upstream, higher smoke temperature is recorded at damper 2 in the downstream. Damper 2 records a smoke temperature of 180°C, whereas damper 1 records a smoke temperature of 75°C. This is because of the 5% road gradient resulting in smoke overshooting well beyond damper 2 in the downstream. In FS 2a, where LV is controlled at 2 m/s, smoke temperatures at damper 1 and damper 2 are 95°C and 140°C, respectively. Compared to FS 1a, smoke temperature in damper 1 is increased because of the reduced supply of ambient air when LV is decreased from 3 m/s to 2 m/s. Smoke temperature in damper 2 is decreased because less smoke is pushed to damper 2 as a result of the reduction in upstream ventilation momentum and the development of reverse flow in the downstream.

5.1.2 Fire scenarios 1b and 2b – with fire suppression

Comparison of the two fire scenarios (FS 1b and FS 2b) with fire suppression and LV controlled at 3 m/s and 2 m/s shows the same effects, as shown in Figures 6-1b and 6-2b. In scenario FS 2b where LV is controlled at 2 m/s enhances the smoke capture by the dampers. Tunnel visibility is quantitatively given in Figures 7-1b and Figure 7-2b.

This analysis shows that LV flow control plays an important role for the successful management of a fire incident. Sufficient LV flow can prevent backlayering in the upstream section for free-flowing traffic conditions. However, excessive LV flow from the upstream can generate excessive flow momentum resulting in smoke flow overshooting beyond the extraction point in the downstream, which can impact on congested traffic conditions. The downstream portion of the tunnel with an uphill gradient is especially vulnerable as stack effects can develop.

5.2 Influence of fire suppression intervention

It is well known that fire suppression can cool down the smoke temperature and disturb the smoke layer stratification. Computer modelling gives quantitative assessment in terms of smoke temperature and the visibility. Average smoke temperature at each individual damper during the HRR fully developed stage is summarized in Table 5.

5.2.1 Fire scenarios 1a and 1b – LV controlled at 3 m/s

The impact of fire suppression can be seen when comparing the smoke temperature of FS 1a and FS 1b, where both have LV controlled at 3 m/s. Figure 8 shows that smoke temperature at each damper extraction point dropped significantly with the intervention of fire suppression system.
In fire scenarios with LV controlled at 3m/s (FS 1a and FS 1b), comparisons given in Figure 8-1a and Figure 8-2a show smoke temperature decreases by 35 °C and 92 °C at damper 1 and damper 2, respectively, if fire suppression is operating.

In FS 1b where LV is controlled at 3m/s and fire suppression is operating, smoke temperature at damper 2 is still much higher than that at damper 1 because of the combined effects of the push from the LV of 3m/s and the stack flow in an uphill ramp. Therefore damper 2 extracts more smoke than damper 1.

However, the impact of fire suppression intervention on visibility is negative when LV is controlled at 3m/s, because suppression leads to smoke layer de-stratification.

For cases with and without fire suppression (FS 1a and FS 1b) and with LV controlled at 3m/s, visibility in Figures 6-1a and 6-1b show an LV flow of 3m/s combined with fire suppression intervention impacts the visibility in the downstream section beyond the damper extraction point at low level. Visibility in the further downstream section beyond the downstream damper extraction point is significantly impacted when fire suppression is operating, as seen when comparing the smoke zone in Figures 7-1a and 7-1b. This is because the fire suppression intervention disturbs the smoke layer and the smoke stays in a lower location beyond the downstream damper.

5.2.2 Fire scenarios 2a and 2b – LV controlled at 2 m/s

Figure 8-1b compares the smoke temperature at the damper extraction point 1 for fire scenarios FS 2a and FS 2b, where LV flow is controlled at 2m/s. Figure 8-2b compares the smoke temperature at the damper extraction point 2 for fire scenarios FS 2a and FS 2b. When compared to FS 2a, smoke temperature decreases by 30 °C and 75 °C at damper 1 and damper 2, respectively, as the fire suppression is operating for FS 2b.

In FS 2b where LV is controlled at 2m/s and fire suppression is operating, the smoke temperature at damper 1 and damper 2 are almost the same. This is because the enhanced damper extraction rate can generate a reverse flow in the downstream, which draws in ambient air from the downstream end. Examination of the visibility shown in Figure 6-2b confirms that a longitudinal ventilation flow of 2 m/s combined with fire suppression intervention enhances the smoke capture at extraction dampers. Smoke is contained within a zone between the two dampers.

For scenarios FS 2a and FS 2b, visibility beyond the damper extraction point is not influenced, as shown in Figures 6-2a and 6-2b. This is because the extraction dampers have an effective capture of the smoke when the LV is reduced to 2 m/s.

The above discussion shows that with fire suppression, smoke temperature can be effectively decreased and longitudinal flow control becomes more critical for maintaining a visibility in the downstream.

5.3 Influence of action delay time of emergency system

The successful management of a fire incident relies not only on robust fire suppression and ventilation systems and a proper emergency management strategy, but also depends on a timely response.

As shown in Figures 7-2a and 7-2b, scenarios FS 2a and FS 2b demonstrate that visibility is not impacted with a response time of 3 minutes. However, in scenarios FS 3a
with FS 3b, as shown in Figures 7-3a and 7-3b, visibility is impacted because of the prolonged response time of 5 minutes.

This has shown that, even though the LV flow control strategy is in place, a response time longer than 5 minute will force occupant to evacuate under smoky conditions in the event of a HGV fire.

6 CONCLUSION

Computer modelling can be used as an aid for the fire and life safety assessment of tunnel fire management strategies.

Computer modelling in the present paper shows that the control of LV airflow, the activation of fire suppression systems and the timely activation of emergency systems play an important role in the successful management of a tunnel fire.

To maintain the visibility in a tunnel fire incident in a congested traffic condition for the example in this paper, the importance of controlling the longitudinal ventilation flow was demonstrated. Controlling longitudinal flow is especially important for systems equipped with an extraction system and a fire suppression system. This is because fire suppression disturbs the smoke stratification layer and may cause smoke to overshoot the smoke extraction points. Control of smoke overshooting the smoke extraction points needs to be managed in a congested traffic condition so it does not impact on safe egress.

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