Fire and Smoke Management in a Uni-Directional Road Tunnel for a Congested Traffic Condition

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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 longitudinal 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 2 m/s can maintain tenable conditions upstream and downstream for congested traffic conditions.

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

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 (Bettelini et al, 2001). For tunnel designers and operators, the most important issue to consider is the protection of the lives of the tunnel occupants (NFPA502, 2004).

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 (Chan, 2003). 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 (Kashef, 2008). 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

Table 1. Fire scenarios under different traffic conditions.

Scenario #	traffic	Tunnel grad	Avoid smoke migration
A	Non-congested	Down hill	upstream
B	Non-congested	0%	upstream
C	Non-congested	Uphill	upstream
D	Congested	Down hill	Upstream & downstream
E	Congested	0%	Upstream & downstream
F	Congested	Uphill	Upstream & downstream

suppression, emergency response time of the operator, 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.

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 in the upstream has been studied extensively by other investigators with well-researched critical velocities to prevent smoke backlayering in the upstream (PIARC, 1999; Kennedy, 1996a; Kennedy, 1996b; Wu, 2000; Kunsch, 2002; Hwang and Edwards, 2005). As such, the investigation of tenability in the upstream is not repeated in the present paper. For the downstream under congested traffic condition, the worst-case scenario is a fire occuring 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 in an 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 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, as shown in Figure 2.

There is a lot of discussion related to fire suppression intervention (Vasilovska, 2006; Carvel, 2009). It is known to be able to control the smoke temperature, but the side effect is it disturbs 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 flow is influenced, when the longitudinal airflow pushes lower-level smoke downstream well beyond the damper extraction point.

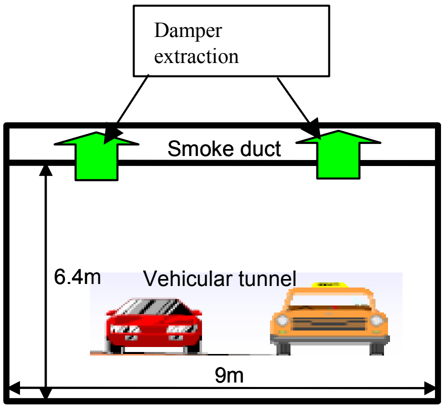


Figure 1. Cross section of the 2-lane road tunnel.

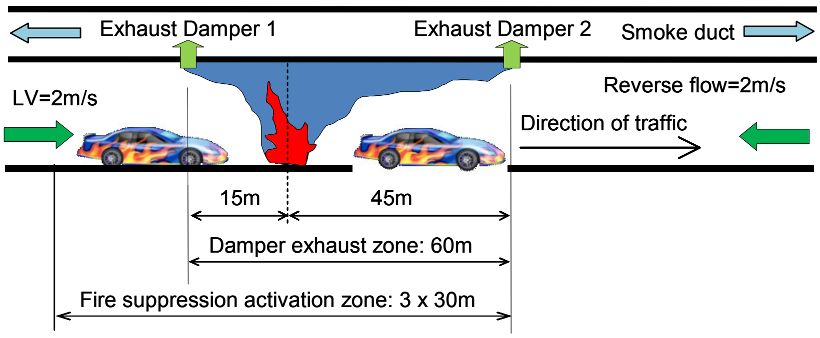


Figure 2. Tunnel fire and smoke management for congested traffic condition.

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 time 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 9 m wide by 6.4 m 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 60 m 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, and its growth rate is assumed based on the reference of the UPTUN test (Ingason and Lonnermaker, 2005; Beard and Carvel, 2005). This fire represents a heavy goods vehicle (HGV) fire. The assumption for the 50 MW fire includes a reduction of fire heat release rate (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 HRR of 2 MW at 3 minute and then the maximum HRR at 6 minute. The design fire is conservatively assumed

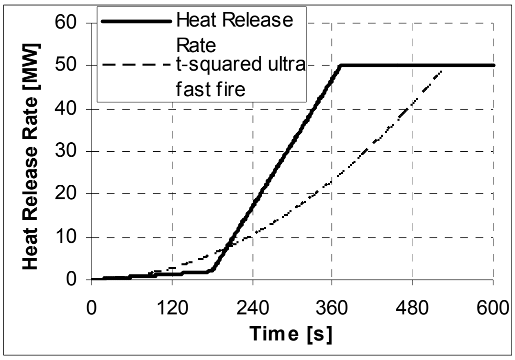


Figure 3. Design fire growth curve and a reference ultra-fast fire curve.

Table 2. Key emergency actions.

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

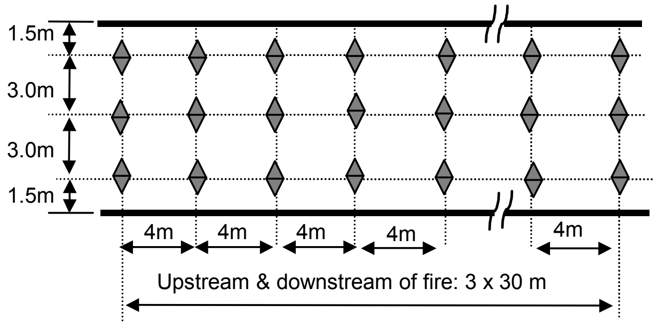
to have a growth rate faster than that of the ultra-fast fire.

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 in a uni-directional traffic tunnel. However, traffic congestion may occasionally occur. When the traffic flow speed drops, the LV airflow is supplemented with 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 minutes 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 considered.

In the event of this example 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 minute2. Fire suppression nozzles covering a 90 m section above the fire, as shown in Figure 2, are assumed to be activated to control the fire within 3 minutes. 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 10 mm/min for the entire 90 m long section, delivering 120 L/min in each nozzle, is assumed. The nozzles are assumed to be spaced 3 m x 4 m below the tunnel ceiling, as shown in Figure 4.

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.



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

Figure 4. Plan of deluge water discharge nozzle.

3. Computer Modelling and Assumptions

The Fire Dynamic Simulator (FDS) (McGrattan, 2008) 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 (Kim, 2008; Liu, 2007; Bilson, 2008; Maele and Merci, 2008; Vidmar and Petelin, 2007), is used in this study.

The feature of FDS is that it has a built-in LES model for modelling turbulence, as well as a feature for combustion calculation. The governing equations used in FDS have been detailed in the FDS Technical Guide, and is not repeated here. The default Smagorinsky constant of 0.2 is used in the modelling and thermal radiation is assumed account for 30% of the total HRR from the fire. A smoke production rate of 10% of the fuel consumption is assumed for calculating the visibility.

The computational domain is a section of the tunnel, which is 240 m long x 9 m wide x 6.4 m high. The initial condition is assumed to be ambient and airflow speed is minimal, the designed longitudinal ventilation is imposed at the tunnel inlet, and downstream is assumed to be open. The number of meshes in three coordinate directions is 480 x 45 x 32, which gives a total number of cells of 691,200. Mesh size resolution is at the same level as discussed in McGrattan et al (1998), which is about one tenth of the characteristic length scale D* when compared with the maximum grid of the three directions.

$$D^*=\left(\frac{HRR}{\rho_\infty T_\infty C_p g^{0.5}}\right)^{0.4}$$

Where ρ_∞, T_∞ and C_p are the density, temperature and the specific heat of the ambient tunnel air respectively, and g is the gravity, 9.81 m/s^2.

Only the 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 conditions are 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 3.5 m x 2 m. This gives a total extract area of 14 m^2 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, which is based on the fact that most of the Australian tunnels that are built with smoke duct extraction systems are designed based on this factor. The reason is that the Thomas correlation (International Fire Engineering Guideline, 2005) can not be used here as the tunnel ventilation is not natural ventilation flow, but dominated by the

Table 3. Fire scenarios considered for congested traffic conditions.

Scenario #	Longitudinal ventilation [m/s]	With/without fire suppression	Ventilation response time [min]
1a	3.0	without deluge	3
2a	2.0	without deluge	3
3a	2.0	without deluge	5
1b	3.0	with deluge	3
2b	2.0	with deluge	3
3b	2.0	with deluge	5

forced longitudinal ventilation along the tunnel and the entrained smoke volume is highly dependent on the longitudinal ventilation

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

Base extraction rate [kg/s] = longitudinal ventilation (LV) [m/s] x tunnel cross section [m^2] x ambient density [kg /m^3]

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

4. Occupants Evacuation

Occupants are designed to egress through the non-incident tube which is connected to the incident tunnel with cross-passages spaced every 120 m 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.

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 30 m of the fire site, Group 2 are those who are more than 30 m away from the fire site. These two groups of

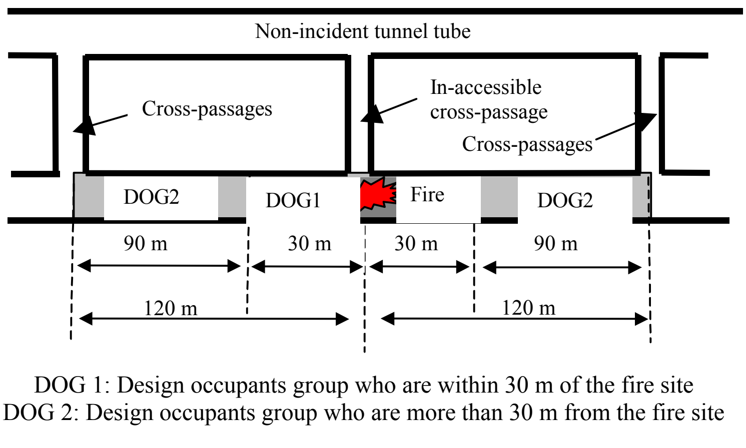


Figure 5. Plan of the tunnel occupants groups and cross-passage emergency exits.

Table 4. Evacuation parameters with egress exits at every 120 m along the tunnel.

Design Occupant Group	Distance from fire [m]	Detection time [s]	Pre-movement time [s]	Maximum travel time [s]	Required Safe Evacuation Time [s]
DOG 1	< 30 m	15	15	120	150
DOG 2	> 30 m	120	30	90	240

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 30 s. 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 150 s. Travel time depends on the travel speed and the travel distance towards the exit. In this paper, we monitor the person from each DOG who is originally located furthest away from the exit, and calculate the length of time that is required to reach each location along the travel route 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 120 s for DOG 1 occupants.

The Required Safe Evacuation Time (RSET) is the sum of detection time, pre-movement time and travel time, and the travel time is a function of location where the monitored occupant has reached. 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 activated extract dampers, as shown in Figure 2. Performance of the damper extraction rate is assessed by examining the visibility at 2.1 m above the tunnel road surface at the tunnel section beyond the two activated damper extraction points. Figure 6 shows the CFD modelling result of visibility on the central plane at 10 minutes after the fire initiation for different scenarios.

Visibility and temperature are recorded from the CFD runs every 5 m along the tunnel longitudinal direction. The monitoring location is 2.1 m above the road surface at the centreline of the tunnel. For this assessment, Available Safe Evacuation Time (ASET) is calculated based on the acceptance

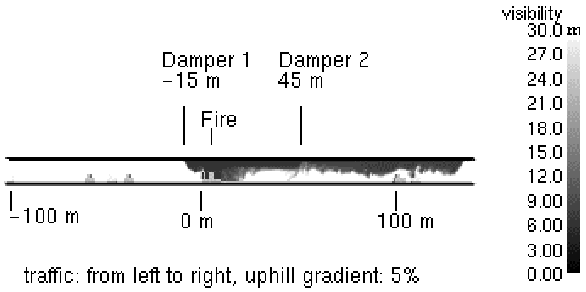


Figure 6-1a. Visibility in metres for LV=3 m/s without fire suppression in FS 1a.

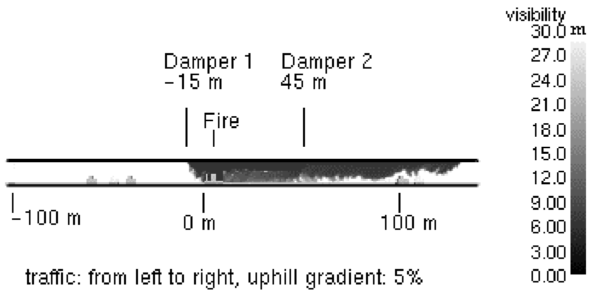


Figure 6-1b. Visibility in metres for LV=3 m/s with fire suppression in FS 1b.

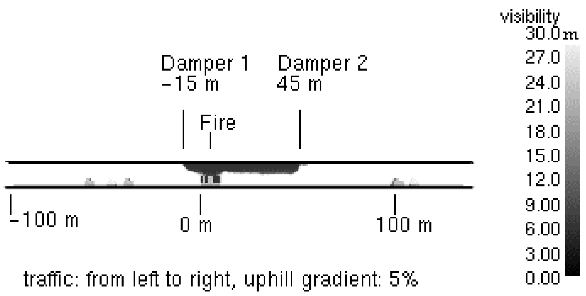


Figure 6-2a. Visibility in metres for LV=2 m/s without fire suppression in FS 2a.

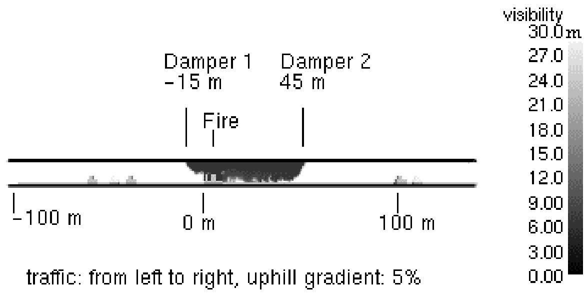


Figure 6-2b. Visibility in metres for LV=2 m/s with fire suppression in FS 2b.

Figure 6. CFD modelling visibility (m) result at 10 minutes after fire initiation for scenarios with LV = 2 m/s and 3 m/s.

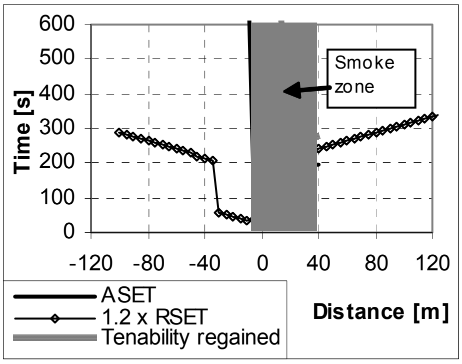


Figure 7-1a. ASET/RSET for FS 1a (without fire suppression, LV=3 m/s, 3 minutes action delay).

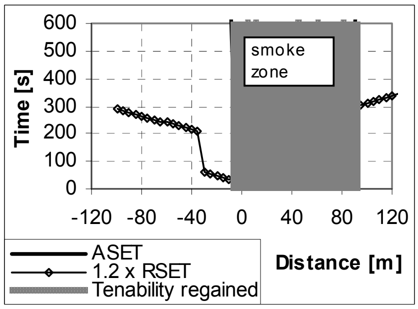


Figure 7-1b. ASET/RSET for FS 1b (with fire suppression, LV=3 m/s, 3 minutes action delay).

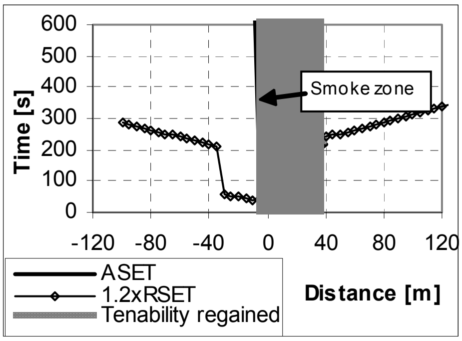


Figure 7-2a. ASET/RSET for FS 2a (without fire suppression, LV=2 m/s, 3 minutes action delay).

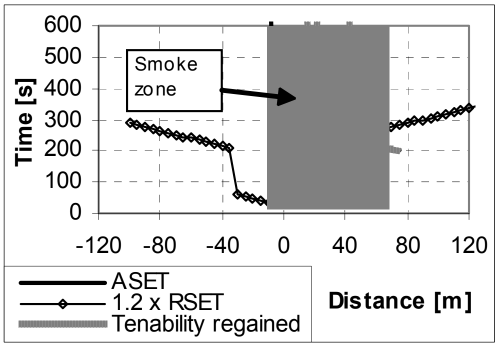


Figure 7-2b. ASET/RSET for FS 2b (with fire suppression, LV=2 m/s, 3 minutes action delay).

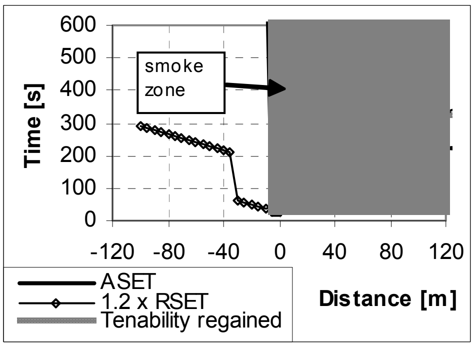


Figure 7-3a. ASET/RSET for FS 3a (without fire suppression, LV=2 m/s, 5 minutes action delay).

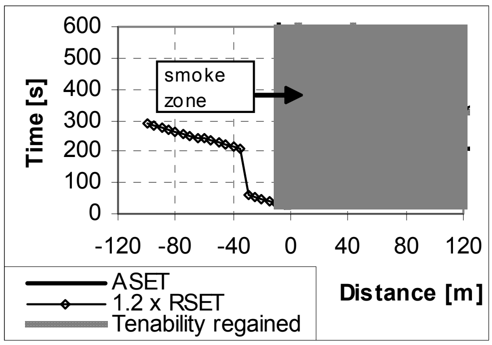


Figure 7-3b. ASET/RSET for FS 3b (with fire suppression, LV=2 m/s, 5 minutes action delay).

Figure 7. RSET and the smoke zone showing when and where visibility drops to 7 m.

visibility criteria of 7 m at 2.1 m above the tunnel floor in accordance with PIARC (1999). It should be noted that this PIARC visibility criteria is only an indication of tenability, as tenability depends on other factors such as CO concentration (Yung, 2008), etc. The smoke zone, which shows when and where in the tunnel the visibility is decreased to 7 m at 2.1 m above the road surface, is given in Figure 7. The 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

Table 5. CFD results of average smoke temperatures at two damper extraction points and visibility conditions.

Scenario #	LV control [m/s]	Deluge	Action delay time [minute]	Damper 1 temperature [°C]	Damper 2 temperature [°C]	Visibility criteria* satisfied?
1a	3.0	N	3	75	180	Y
2a	2.0	N	3	95	140	Y
3a	2.0	N	5	95	140	N
1b	3.0	Y	3	40	88	N
2b	2.0	Y	3	65	65	Y
3b	2.0	Y	5	65	65	N

flow rate and mass flow rate passing through the damper openings. This calculated temperature is the average bulk gas temperature as the combustion products and the ambient air drawn into the smoke duct will be mixed, this average bulk gas stream temperature is an important reference for the fire safety design of the smoke duct. The transient smoke temperature development at damper 1 and damper 2 are shown in Figure 8.

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 at the 2.1 m level 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 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, the smoke capture is enhanced by the dampers. Tunnel visibility is quantitatively given in Figures 7-1b and 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 over-shooting 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 develop.

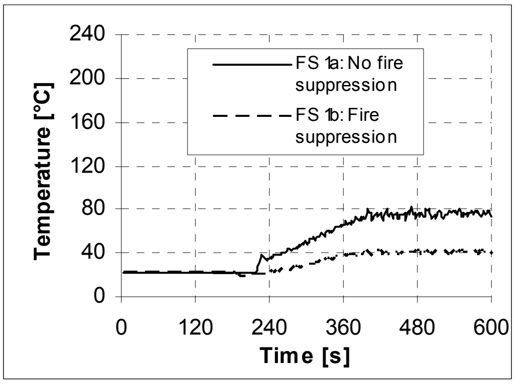


Figure 8-1a. Smoke temperature at extraction point damper 1 for FS 1a and FS 1b [LV=3 m/s].

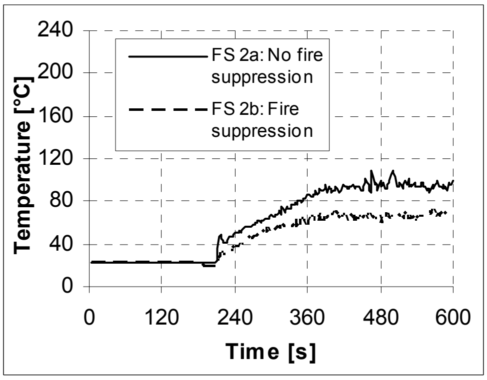


Figure 8-1b. Smoke temperature at extraction point damper 1 for FS 2a and FS 2b [LV=2 m/s].

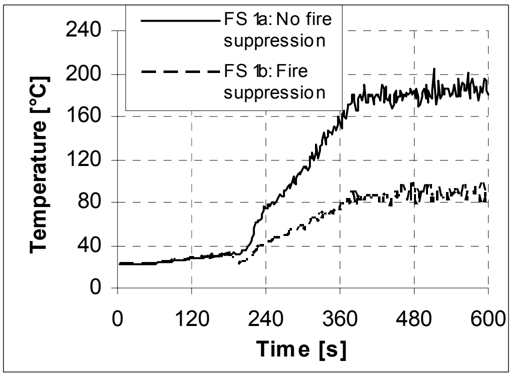


Figure 8-2a. Smoke temperature at extraction point damper 2 for FS 1a and FS 1b [LV=3 m/s].

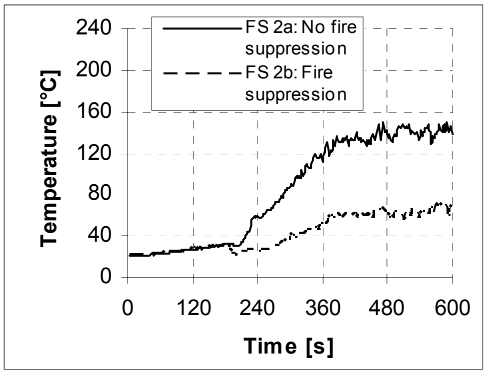


Figure 8-2b. Smoke temperature at extraction point damper 2 for FS 2a and FS 2b [LV=2 m/s].

Figure 8. Smoke temperature at damper extraction points.

5.2 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 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 the fire suppression system.

In fire scenarios with LV controlled at 3 m/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 3 m/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 3 m/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 3 m/s, because suppression leads to smoke layer de-stratification.

For the 3 m/s LV cases with and without fire suppression (FS 1a and FS 1b), visibility in Figures 6-1a and 6-1b shows an LV flow of 3 m/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 damper extraction point 1 for fire scenarios FS 2a and FS 2b, where LV flow is controlled at 2 m/s. Figure 8-2b compares the smoke temperature at 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 2 m/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 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 minutes will force occupants to evacuate under smoky conditions in the event of a HGV fire.

6. Conclusions

Computer modelling can be used as an aid for the fire and life safety assessment of tunnel fire management strategies, and this example case has presented a methodology on how to give quantitative risk assessment of a tunnel fire and life safety.

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, 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.

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
DOG – Design occupants group
RSET – required safe evacuation time
PIARC – Permanent International Road Association

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