A Methodology for Assessment of Visibility during Road Tunnel Fires

YUNLONG LIU,* VIVEK APTE, YEN LUONG, XIJUAN LIU
AND DAVID YUNG

Fire Science and Technology Laboratory
CSIRO Manufacturing and Infrastructure Technology
PO Box 310, North Ryde, NSW 1670, Australia

ABSTRACT: This article presents a methodology for evaluating life safety risks due to lack of visibility in road tunnel fires. The methodology considers three realistic fire scenarios that involve smoke spread, occupant evacuation, and the reliability of fire suppression systems. The three fire scenarios represent three variations of fire growth rates. The road tunnel, in this study, is assumed to have two traffic tubes, a longitudinal ventilation system, and emergency exits and escape routes. The Fire Dynamics Simulator (FDS) software is used to model smoke spread and the time available for evacuation, based on a visibility limit when occupants cannot find their way to the emergency exits. A simple evacuation model is used to estimate the time required for occupants upwind of the fire to egress through the emergency exits. Vehicles downwind of the fire are assumed to continue moving and exit the tunnel safely. In two of the three fire scenarios, conditions in the tunnel become untenable rapidly, not allowing sufficient time for the occupants to egress safely. A simple risk assessment is used to estimate the number of fatalities, based on the number of occupants who are trapped in untenable conditions in the tunnel. The assessment indicates that a reliable fire suppression system could prevent heavy casualties in a tunnel fire.

KEY WORDS: tunnel fires, life safety, evacuation, fire suppression, visibility.

INTRODUCTION

ACCIDENTAL FIRES IN a tunnel can have disastrous consequences in terms of loss of life and property [1]. Recent major tunnel fire incidents in Europe include fires in the Mont Blanc tunnel [2], Tauern Range tunnel, Gleinhalm tunnel, and Gotthard tunnel. The Gotthard tunnel fire involved

---

*Author to whom correspondence should be addressed. E-mail: Yunlong.Liu@csiro.au

1042-3915/07/01 0065–15 $10.00/0 DOI: 10.1177/1042391507064995

thirteen trucks, four vans, and six cars. Inadequate ventilation had been identified as one of the possible reasons [3] for a prolonged exposure of occupants upstream of a fire to the backflow of hot and toxic smoke. Factors which can influence smoke spread in the event of a tunnel fire include tunnel geometry, ventilation rate, fire location, fire size, and growth rate.

Numerous research papers have been published recently on tunnel fire safety and related topics. Ingason and Wickstrom [4] suggest that active and passive fire suppression should be used together to improve fire safety in road tunnels. Fire suppression systems have been designed and installed in some tunnels in Japan, Europe, and other places, and the US has seen a few applications. Tunnel fire safety under longitudinal, transverse, and various combinations of longitudinal and transverse ventilation systems have been investigated using computational fluid dynamics (CFD) fire-smoke models [3,5]. Modic [6] conducted fire simulations in road tunnels and has also discussed evacuation strategies. Apte et al. [7] measured burning rate, temperature field, and smoke backflow in a series of pool fire tests in a ventilated tunnel. The validation study of a CFD model using realistic, transient design fires, based on the memorial tunnel fire ventilation test program (MTFVTP), is given in [8], which has demonstrated good consistency between the numerical and test results. However, risk assessment methodologies have not been found that include realistic fire scenarios, smoke spread, occupant evacuation, and reliability of fire suppression systems in the event of a tunnel fire.

This article presents a comprehensive methodology for evaluating life safety risks due to lack of visibility in a road tunnel in the event of a fire. The methodology considers not only realistic fire scenarios and smoke spread, but also occupant evacuation and the reliability of fire suppression systems. Three realistic fire scenarios, representing three variations of fire growth rates, are used. Smoke backflow is computed using the fire dynamics simulator (FDS) [9]. The available safe egress time is obtained based on a visibility limit that implies occupants cannot find the emergency exits. This limit is assumed to be a distance of 10 m at a height of 2.1 m from the floor, and occupants are assumed to be trapped if visibility is below this limit. Evacuation of tunnel occupants is estimated using a simple evacuation model. The dependence of visibility on fire size, fire growth rate, and fire suppression system reliability is then discussed. The objective thus is to present a methodology that can provide an analysis of the major factors causing fire deaths just due to lack of visibility in tunnels, and also options for fire safety engineers to minimize loss of life. The methodology can be used to show why some fires lead to loss of life and to identify protection systems to minimize this loss.

TUNNEL GEOMETRY AND TRAFFIC CONDITIONS

The tunnel chosen for this study is assumed to represent a typical tunnel, with two separate tubes for unidirectional traffic in opposite directions. Each tube has two traffic lanes, 2300 m long × 6 m high × 8.6 m wide. For simplicity, no vertical gradient along the tunnel length is assumed. Emergency exits for occupants, 1.2 m wide × 2 m high × 10 m long, are assumed to be provided at every 120 m along the tunnel length. These exits provide cross passages between the two tubes. If there is a fire in one tube, occupants will be evacuated into the other. The fire in one tube is assumed not to affect the other tube. The longitudinal ventilation rate is assumed to be at 2.5 m/s under normal operating conditions, but can be increased up to 10 m/s along the traffic direction.

The number of vehicles and occupants in the tunnel during traffic hours can be estimated. Assuming the two-traffic-lane tunnel is packed with vehicles and assuming a tunnel length of 5 m per car, 10 m per bus, and one bus for every 10 cars, there could be a total of 383 cars and 38 buses per tube. Assuming also an average of 2 occupants per car and 30 occupants per bus, there could be a total of 1906 occupants in each tube, or about 100 occupants per 120 m section between evacuation exits. In the event of a fire incident, the vehicles upwind of the fire are forced to stop because of the traffic blockage at the fire location. All the vehicles downwind of the fire are assumed to drive away at about 60 km/h, i.e., 16.7 m/s, sufficient to be ahead of the advancing smoke front and, therefore, exit the tunnel safely. This is an optimistic assumption. If there is a traffic jam on the downstream side and the vehicles cannot move away faster than the rate of smoke spread, then fire deaths will be higher. The concern, therefore, is mainly for the occupants in the vehicles upwind of the fire, especially for those who are close to the fire location, as these occupants would be exposed to the hot, toxic smoke unless they can escape quickly through the emergency exits.

FIRE SIZE AND LOCATION

Table 1 and Figure 1 summarize the three fire scenarios that are used in the present analysis. The three scenarios (A, B, and C) are based on heat

Table 1. List of tunnel fire scenarios (see Figure 1 for HRR profiles).

Fire scenario	Peak fire size (MW)	Reference fire test
A	33.2	Car fire test [10]
B	33.2	Pool fire test in a tunnel [7]
C	35.0	Coach fire test [11]

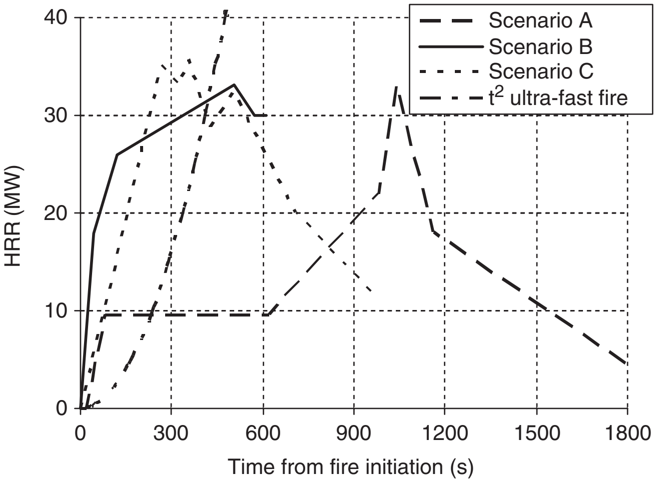


Figure 1. *HRR profiles of design fires used for FDS calculations (see Table 1 for details).*

release rate (HRR) measurements conducted in real-scale fire tests [7,10,11]. In the FDS calculation, the burning area is assumed for all the scenarios to be 8 m^2. The HRR profiles are shown in Figure 1. Peak HRRS used here are relatively low when compared to results from recent vehicle fire tests in a tunnel [12], where the peak HRR are estimated to be around 200 MW. The use of typical small fires is to provide a conservative analysis of whether current fire protection strategies are adequate. If the strategies are not adequate for small fires, then they would definitely be inadequate for larger fires.

Scenario A is based on the HRR measured in a series of car fire tests [10]. The car had been ignited with 1.5 L gasoline in an open tray under the left front seat. The left front window is completely open, and the right front window is half open. All the doors are closed. The HRR is measured using the oxygen depletion technique by collecting all the fire products in a hood covering the burning car. For the present study, the peak HRR measured originally is scaled up from 8.3 to 33.2 MW to represent a fire following a crash involving a car and a bus. It is assumed that a bus fire is equivalent to a fire involving three cars.

Scenario B is based on the measured HRR from a 2 m diameter pool fire in a 2.4 m high × 5.4 m wide × 120 m long tunnel under a 1.5 m/s ventilation airflow speed [7]. The HRR in this test reached a peak value of 14.7 MW within 9 min of ignition, and a HRR per unit area of 4.15 MW/m^2 [7]. Assuming the same HRR per unit area can be applied for scenario B, the peak HRR for a burning area of 8 m^2 is 33.2 MW. This represents a burning fuel pool formed by a spill from vehicles following a crash.

Scenario C is based on the HRR measurement of a burning coach, 18 m long × 2.8 m wide × 3 m high, with 40 seats [11]. The HRR increases to 35 MW within 5 min of ignition, and decreases quickly 10 min after ignition.

The HRR profiles in Figure 1 are the design fires used as inputs to the FDS model to calculate smoke spread into the tunnel for scenarios A, B, and C. The t^2 ultra-fast fire growth curve in Figure 1 is added to provide a reference for the fire growth rates of the three scenarios. For the present study, the fire is assumed to have occurred conservatively at the center of the tunnel and near an emergency exit, for all scenarios. The location at an exit represents the worst-case scenario for the cars immediately upwind of the fire because the occupants have to travel the full 120 m to get to the next upwind exit.

PREDICTION OF SMOKE SPREAD AND TIME AVAILABLE FOR EGRESS

To study the effect of fire on life safety, the FDS [9] is used to predict smoke spread in the tunnel for scenarios A, B, and C. The accuracy of the FDS predictions have been examined previously against the measurements of smoke transport in a model tunnel in Lee and Ryou's work [13]. The FDS calculation is also checked here against a smoke backflow test generated by a 2.5 MW pool fire in a ventilated tunnel [7]. Figure 2 shows a comparison of the FDS predictions and the experimental data on smoke backflow distance at different times after fire ignition. It can be seen that the FDS predictions of the smoke back-layering distance for this experiment are within ±20%

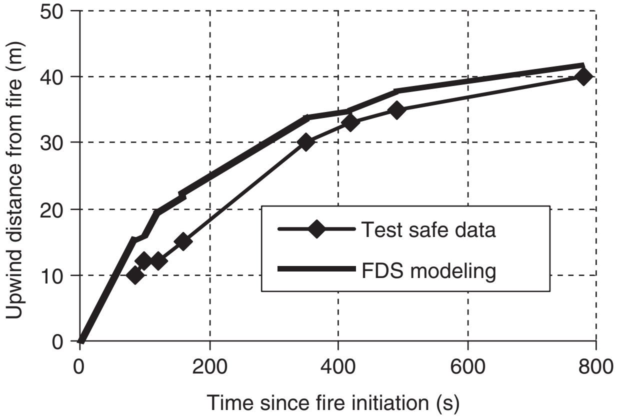


Figure 2. *Validation of FDS in terms of smoke backflow distance from pool fire test data [7].*

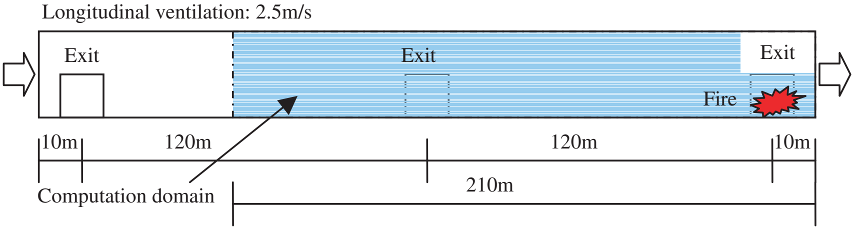


Figure 3. *Schematic of computational domain (side view and not to scale). (The color version of this figure is available online.)*

of the measurements. This comparison confirms the suitability of using FDS for the present study.

To determine the effect of the three fire scenarios, the computational domain is chosen to be 210 m long, as shown in Figure 3. The fire was located at an emergency exit and at 10 m upwind of the downwind end of the computational domain, allowing smoke backflow to be computed over a distance of 200 m. The 200 m long domain covers the critical section between the fire and the next upwind exit 120 m away. Occupants from further upwind 120 m sections can evacuate more readily than those in the immediate 120 m section next to the fire. The computational domain was limited to 200 m upwind of the fire to save computational time. Additional runs with FDS using much larger computational domains were conducted which extended up to 120 m downwind of the fire. It was found that this does not alter the results. The domain also covers the entire tunnel cross-section and extends 0.5 m into the walls, ceiling, and the floor. Vehicles downwind of the fire are assumed to drive out of the tunnel safely, ahead of the smoke front.

A constant and uniform 2.5 m/s velocity profile is applied at the upwind inlet in the computational domain, as shown in Figure 3. This constant ventilation rate assumes that the ventilation rate cannot be easily increased. Higher ventilation rates can be considered if they are needed. A higher ventilation rate may help prevent smoke backflow in the upwind direction, but may increase smoke spread in the downwind direction.

For the three scenarios, heat is assumed to be released uniformly over a fuel area of 8 m^2 at the fire location. It is also assumed that the smoke yield is 10% of the fuel burning rate. Hence, the visibility is dependent on the fuel burning rate, which is related to the HRR.

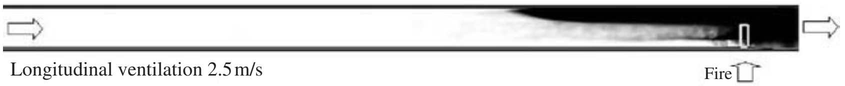
To analyze the time-dependent development of untenable conditions upwind of the fire, the visibility and gas temperature at 2.1 m [14,15] above the floor are calculated using FDS at 10 locations. These locations are at 0, 5, 10, 20, 40, 60, 80, 100, 120, and 140 m upwind of the fire, along the longitudinal centerline of the tunnel.

A sensitivity study on the grid size is carried out, which indicates that a fine grid of 250 × 45 × 62 mm is necessary to get grid-size independent results. The grid size used for all scenarios are (i) a fine grid of 200 × 160 × 160 mm, corresponding to tunnel length, width, and height respectively, in the region within 2 m from the fire, (ii) a coarse grid of 500 × 160 × 160 mm up to 75 m upwind of the fire and 2 m downwind of the fire, and (iii) an even coarser grid of 1200 × 160 × 160 mm for the region beyond 75 m from the fire. Time step length was adjusted so that the CFL condition [9] was satisfied. The time-averaged time step used in the present computation was 0.01 s. To compute 600 s of a fire scenario, 14 days were required to run FDS version 4.03 on a personal computer with a single Pentium 4, 2.0 GHz processor.

Figure 4 shows the predicted smoke backflow at 180 and 300 s from the start of a fire for scenarios A, B, and C. The parameter used to characterize visibility through smoke is the soot density. Clearly, the growth rate of the HRR (Figure 1) has a significant impact on the smoke backflow. The smoke backflow is the slowest for scenario A and the fastest for scenario B. At 180 s from the start of the fire, the smoke back-layer travels approximately 40 m, 110 m, and 70 m from the fire for scenarios A, B, and C, respectively. At 300 s, the smoke back-layer travels 50 m, 120 m, and 106 m from the fire for scenarios A, B, and C, respectively. The maximum distances that the smoke travels in the upwind direction for scenarios A, B, and C are 123 m at 1150 s, 123 m at 540 s, and 124 m at 390 s, respectively. This shows that the HRR curve affects the smoke back-layering significantly. It is, therefore, important to have a realistic HRR curve in order to carry out a proper safety assessment of a tunnel fire.

Local visibility is the maximum distance an occupant can see at eye level. In this study, the eye level is assumed to be at 2.1 m from the ground [14,15]. Figure 5 compares the time when the local visibility decreases to 25 m at different locations upwind of the fire for scenarios A, B, and C. The time is longer for scenario A than scenarios B and C. For example, at 5 m upstream of the fire, it takes more than 10 min for the local visibility to decrease to 25 m for scenario A; whereas it takes only about 1 min for both scenarios B and C. At 120 m upstream of the fire, it takes 18 min for the visibility to drop to 25 m for scenario A, whereas, it takes only 5 min for scenarios B and C.

According to fire safety engineering standards [14,15], occupants are disorientated and have difficulty in making decisions on escape direction if visibility drops below 10 m. Once occupants cannot see to escape, they become trapped in the tunnel and life risks are then implicit as a result of the heat and toxicity that follow. Therefore, toxicity is not considered explicitly in the present analysis. Instead, the 10-m visibility criterion is used to



Scenario A, time from fire initiation: 180 s

Scenario A, time from fire initiation: 300 s

Scenario B, time from fire initiation: 180 s

Scenario B, time from fire initiation: 300 s

Scenario C, time from fire initiation: 180 s

Scenario C, time from fire initiation: 300 s

Figure 4. *Side view of smoke back-layering for scenarios A, B, and C (total length shown: 130 m with 120 m upwind and 10 m downwind of the fire). Scenario A, time from fire initiation: 180 s.*

calculate the tenability time, also called the available safe egress time (ASET) [14].

Figure 6 shows ASET as a function of the distance upstream of the fire for scenarios A, B, and C. The calculated results show that, for scenario A, about 13–20 min are available for occupants to evacuate, depending on their specific location. In scenario B, less than 1 min is available for evacuation for those who are within the first 5 m upwind of the fire and 2–5 min are

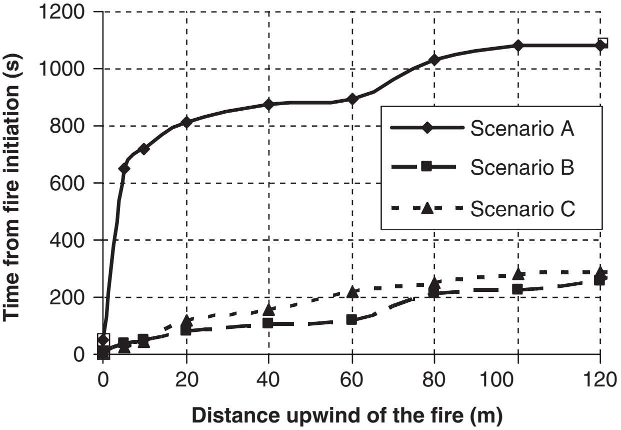


Figure 5. *Comparison of predicted times when visibility drops to 25 m for scenarios A, B, and C.*

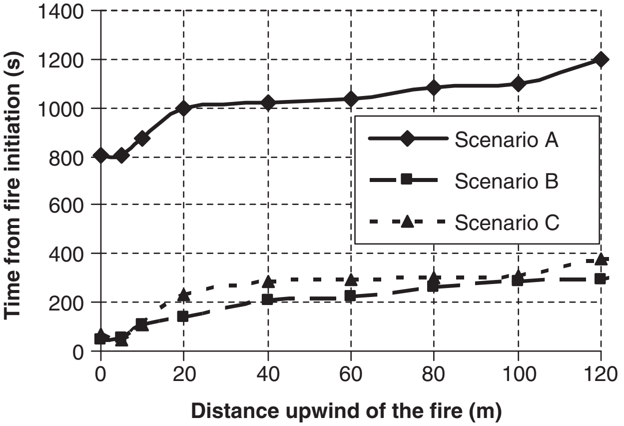


Figure 6. *Comparison of ASET ([time when visibility drops to 10 m]) for scenarios A, B, and C.*

available for those located 20–120 m upwind of the fire. In scenario C, only 50 s is available for occupants who are located within 5 m upwind of the fire, and 3–6 min are available for those who are located beyond 20 m upwind of the fire.

OCCUPANT EVACUATION

Occupant safety depends on whether the occupants can indeed evacuate safely within the ASET. The time required for the occupants to evacuate is called required safe egress time (RSET). In the present analysis, RSET is assumed to consist of three components: cue time; response time; and travel time.

Cue Time

The cue time is the time at which an occupant becomes aware of a fire. In a tunnel, the occupants close to the fire become aware of the fire by the visual cue of flames and smoke. However, where smoke detection is not provided, it may take a long time before occupants remote from the fire become aware of the fire.

In the present analysis, it is assumed that the occupants are alerted when the smoke visibility at the eye level drops to below 25 m, thus providing the visibility cue. However, if the back-layering is controlled and the smoke does not spread too far upwind of the fire, the cue time could be very long. Occupants may still receive other cues such as that from fire alarm signals, car radio communications, vehicles being stationary or evacuating occupants moving away from the fire. In this instance, the maximum cue time is assumed to be 300 s, as a reasonably optimistic approximation.

Response Time

The response time (or 'delay time to start') is the time it takes for the occupants to initiate their evacuation movements once they have perceived some cues of the fire. The time to start depends mainly on the warning system within the tunnel, the proximity of the occupants to the fire, and the characteristics of the occupants.

The estimated response times for various occupancies and warning systems [16] are shown in Table 2, where,

W1: live instructions using a voice communication system from a control room with a closed circuit television facility, or live instructions in conjunction with well-trained, uniformed staff that can be seen and heard by all occupants.

Table 2. Estimated delay time to start evacuation in minutes.

Occupancy type	W1	W2	W3
Offices, commercial, schools, universities	<1	3	>4
Shops, museums, sport and assembly buildings	<2	3	>6
Dormitories, residential mid and high rise	<2	4	>5
Hotels and boarding houses	<2	4	>6
Hospitals, nursing homes	<3	5	>8

W2: noninstructive voice message (prerecorded) and/or informative warning visual displays with trained staff.

W3: warning system using fire alarm signal and staff with no relevant training.

Without detailed knowledge of the human behavior in tunnels, the reluctance of occupants to leave their belongings (in this scenario, their 'vehicle') in an unfamiliar environment is understandable. Thus, in a road tunnel, it is likely that the response time for occupants remote from the fire can be as long as 10 min. However, in the most optimistic scenario, where a W2 system is provided in an unfamiliar environment, a 3-min response time can be assumed similar to that for a museum or a large assembly building.

Travel Time

The travel time is the time taken for all occupants to reach a safe place. This is considered to be the entry into the cross passages that lead into the other running tunnel. The travel time is composed of the time taken to walk to a safe place. For simplicity, the time spent queuing to pass through the cross passage has been ignored. The occupants are assumed to be typical of the general public varying in age and ability, thus, an average travel speed of 0.8 m/s is assumed.

ASET/RSET ANALYSIS

The results of the evacuation time for occupants at discrete locations upwind of the fire for scenarios A, B, and C are shown in Figures 7–9, respectively. The ASET is calculated from the FDS predictions of smoke

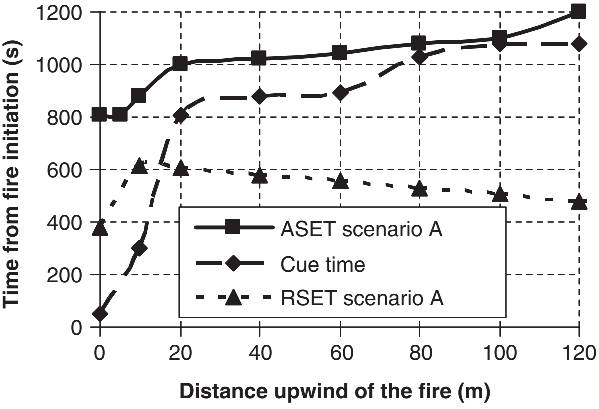


Figure 7. Scenario A: ASET vs RSET analysis.

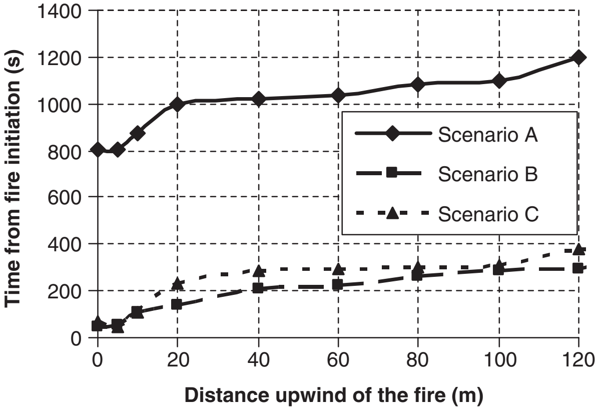


Figure 8. Scenario B: ASET vs RSET analysis.

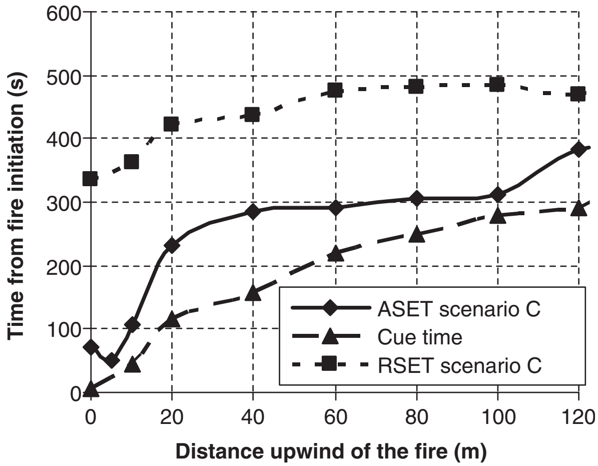


Figure 9. Scenario C: ASET vs RSET analysis.

backflow, and the time for untenable conditions, whereas RSET is calculated from a summation of the cue, response, and travel times.

It can be observed that the occupants considered in scenario A have more than sufficient time to evacuate from the incident tunnel before untenable conditions occur, because RSET $\ll$ ASET. However, in scenarios B and C, RSET $\gg$ ASET, therefore, untenable conditions arise rapidly and most occupants will be evacuating through the low visibility smoke.

According to Figure 7, only those who are close to the accident will be influenced in scenario A, as the ASET is longer than the RSET. However, Figures 8 and 9 show that ASET values are all shorter than RSET values in scenarios B and C. Thus, all of the 100 occupants in the 120 m section adjacent to the fire will be at risk under the conditions discussed here.

FIRE SUPPRESSION RELIABILITY AND RISK ASSESSMENT

The previous section shows that for scenarios such as B and C, the occupants immediately upwind of the fire will not have sufficient time to evacuate and will be at risk. The first 120 m between exits, as shown previously, has about 100 occupants. Just using this section, one single accident involving a moderate fire will result in an expected death toll of at least 100. In this analysis, the occupants beyond 120 m upwind of the fire were not considered.

According to fire statistics [1], about 5.7 fire accidents occur in road tunnels per 100 million km driven. The average number of vehicles passing through the Sydney Harbor Tunnel in 2002 was 87,529 per day [17], or about 31.9 million vehicles per year. The tunnel in the present study is 2.3 km. Assuming the same number of vehicles passing through the tunnel, the kilometers driven per year is 73.5 million. Based on 5.7 fire accidents per 100 million km driven in a tunnel, the expected number of accidents is 4.2. Assuming these accidents are mainly those represented by scenarios A, B, and C and that all these scenarios occur with equal frequency, then two-thirds of the fires can be fatal fires. Considering only those occupants in the immediate 120 m upstream section to the fire are at risk, the expected number of deaths per year is $4.2 \times (2/3) \times 100 = 280$. If the tunnel is longer, or the fire is larger, the expected number of deaths increases proportionally. It should be emphasized that the number of fatalities estimated is only indicative of what could happen in the event of scenarios discussed here, with no fire suppression.

One way to minimize the fire risk in tunnels is to employ reliable suppression systems. If a suppression system is installed and is 100% reliable and effective, no fire can develop into a major event and therefore will not pose a risk. However, if fire suppression is only 80% reliable and effective in controlling accidents, 20% of fires would still develop into accident events that can pose risk to occupant's lives in the tunnel. Under these conditions, the potential number of fatalities would be 20% of 280, i.e., 56, which is still a large number that would not be accepted by society. The loss can increase if the tunnels are longer. If the reliability and effectiveness is increased to 99%, the risk is reduced to 2.8 expected deaths per year. Reliability and effectiveness of suppression systems are therefore important elements in tunnel fire safety. They depend on proper design, testing, and regular maintenance.

CONCLUSION

This article presents a methodology and a preliminary analysis to evaluate life safety in a road tunnel during a fire accident. A typical road tunnel was examined under realistic fire scenarios using CFD modeling, egress modeling, and risk assessment. The rate of fire growth and the reliability of the fire suppression system were found to be the critical factors affecting life safety in a tunnel. For two scenarios with fast growing fires, the analysis shows that the tunnel segment near the fire becomes untenable very rapidly, providing insufficient time for occupants to react and escape. Safe egress of occupants is possible when fire development is slow, as was shown in one scenario with a slow growing fire. For the fast growing fires, an effective fire suppression system is vital in allowing the occupants to escape safely.

ACKNOWLEDGMENTS

The authors would like to thank the National Institute of Standards and Technology (NIST) in the US for providing the FDS software package, and the Road Transportation Authority (RTA) in New South Wales, Australia for providing the tunnel data and design parameters.

REFERENCES

1. Haack, A., ‘‘Current Safety Issues in Traffic Tunnels,’’ Tunnelling and Underground Space Technology, Vol. 17, No. 2, 2002, pp. 117–127.
2. Duffé, Pierre and Marec, Michel, ‘‘Task Force for Technical Investigation of the 24 March 1999 Fire in the Mont Blanc Vehicular Tunnel,’’ Minister of the Interior, Ministry of Equipment, Transportation and Housing, France, 30 June 1999.
3. Li, J.S.M. and Chow, W.K., ‘‘Numerical Studies on Performance Evaluation of Tunnel Ventilation Safety Systems,’’ Tunnelling and Underground Space Technology, Vol. 18, No. 5, 2003, pp. 435–452.
4. Ingason, H. and Wickstrom, U. ‘‘Future Actions for Improving Road Tunnel Fire Safety,’’ FORUM for International Cooperation in Fire Research, FM Global, Norwood, MA, USA, October 2004.
5. Gao, P.Z., Chow, W.K. and Fong, N.K., ‘‘Large Eddy Simulation for Studying Tunnel Smoke Ventilation,’’ Tunnelling and Underground Space Technology, Vol. 19, No. 6, 2004, pp. 577–586.
6. Modic, J., ‘‘Fire Simulation in Road Tunnels,’’ Tunnelling and Underground Space Technology, Vol. 18, No. 5, 2003, pp. 525–530.
7. Apte, V.B., Green, A.R. and Kent, J.H., ‘‘Fire Plume Flow in Mines,’’ NERD&D Project No. 1078, TestSafe Australia, June 1991.
8. Karki, K.C., Patankar, S.V., Rosenbluth, E.M. and Levy, S.S., ‘‘CFD Model for Jet Fan Ventilation Systems,’’ In: Proceedings of the 10th International Symposium on Aerodynaics and Ventilation of Vehicle Tunnels, Boston, MA, USA, November 2000.

9. McGrattan, K.B., "Fire Dynamics Simulator (Version 3) – Technical Reference Guide," National Institute of Standards and Technology, USA, 2005.
10. Joyeux, D., "Car Fire Tests in Closed Car Parks," INC-96/294d –DJ/NB, August 1997.
11. Ingason, H., "Heat Release Rate Measurement in Tunnel Fires," In: Proceedings of the International Conference on Fires in Tunnels, Boras, Sweden, October 10–11, 1994, pp. 86–103.
12. Ingason, H. and Lonnermark, A., "Recent Achievements Regarding Measuring of Time-heat and Time-temperature Development in Tunnels," In: 1st International Symposium on Safe and Reliable Tunnels, FIT-UPTUN-DART Prague, 4-Feburary, 2004.
13. Lee, Sung Ryong and Ryou, HongSun, "A Numerical Study on Smoke Movement in Longitudinal Ventilation Tunnel Fires for Different Aspect Ratios," In: Building and Environment, Vol. 41, 2006, pp. 719–725.
14. Fire Engineering Guidelines, Fire Code Reform Centre Limited, Sydney, ISBN0733704549, March 1996.
15. Fire Safety Engineering in Buildings, British Standard Institution, 1997.
16. Proulx, G., "Movement of People: The Evacuation Timing," In: SFPE Handbook of Fire Protection Engineering. National Fire Protection Association, Quincy, Third Edition, Section 3-Chapter 13, MA, USA, 2002.
17. Annual Average Daily Traffic (AADT) Data, Sydney Region, Road Traffic Authority, NSW, 2002.