Road Tunnel Fire and Life Safety Issues

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ABSTRACT:

This paper evaluates fire and life safety issues in a road tunnel using three fire scenarios. The three fire scenarios represent 3 levels of fire severity. 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 is used to model smoke spread and the time available for evacuation. A simple evacuation model is used to estimate the time required for people 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 people to egress safely. A simple risk assessment approach is used to estimate the number of fatalities. The assessment shows that the level of fatalities depends very much on the reliability and effectiveness of the installed fire suppression system. It is argued that a rapid and reliable fire suppression system is critical in preventing heavy casualties in a tunnel fires.

KEYWORDS: Tunnel fires, life safety, evacuation, fire suppression

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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, Tauern Range Tunnel, Gleinhalm Tunnel and Gotthard Tunnel. The Gotthard Tunnel fire involved thirteen trucks, four vans and six cars. Inadequate ventilation was identified as one of the possible reasons [2] for a prolonged exposure of people 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 [3] suggest that active and passive fire suppression should be used together to improve fire safety in road tunnels. Tunnel fire safety under different ventilation conditions has been investigated using Computational Fluid Dynamics (CFD) fire-smoke models [2, 4]. Modic has conducted fire simulation in road tunnels, and has also discussed evacuation strategies [5]. Apte et al [6] have measured burning rate, temperature field and smoke backflow in a series of pool fire tests in a ventilated tunnel. However, publications on life safety assessment in the event of a tunnel fire, using realistic, transient design fires are not found in the recent literature.

This paper presents a methodology to evaluate life safety in a road tunnel in the event of a fire. Three realistic fire scenarios, representing three levels of fire severity, are studied. Smoke backflow is computed using the Fire Dynamics Simulator (FDS) [7]. The evacuation time of tunnel occupants is estimated using a simple evacuation model. The number of potential fatalities is then estimated. The dependence of life safety on fire growth rate, fire size, and reliability of fire suppression system are discussed.

TUNNEL GEOMETRY AND TRAFFIC CONDITIONS

The tunnel chosen for this study is assumed to represent a typical tunnel, 2300 m long x 6 m high x 8.6 m wide. For simplicity, no vertical gradient along the tunnel length is assumed. The tunnel is assumed to have two tubes, for unidirectional traffic in opposite directions. Emergency exits, 1.2 m wide x 2 m high x 10 m long are assumed to be provided at every 120m along the tunnel length. The fire is assumed to occur in one of the tubes, and not affect the other tube. The longitudinal ventilation rate is

at 2.5m/s under normal operating conditions, but can be increased up to 10m/s along the traffic direction.
The number of vehicles and people in the tunnel during traffic hours can be estimated. Assuming the 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 people per car and 30 people per bus, there could be a total of 1906 people in each tube, or about 100 people per 120 m section between evacuation exits. In the event of a fire accident, the traffic upwind of the fire is assumed to stop moving. 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. The concern is therefore mainly for the people in the vehicles upwind of the fire, as these people would be exposed to hot, toxic smoke unless they can escape quickly through the emergency exits.

FIRE SIZE AND LOCATION

Table 1 and Fig. 1 summarise the three fire scenarios that are used in the present analysis. The three scenarios (A, B and C) are based on heat release rate (HRR) measurements conducted in real-scale fire tests [6, 8 and 9]. In the computer analysis, the burning area is assumed for all the scenarios to be $8m^2$. The HRR profiles are shown in Fig. 1. They are relatively small when compared to the recent vehicle fire tests in a tunnel [10], where the peak HRR was estimated to be around 200MW. The use of typical small fires provide a conservative analysis of whether current fire protection strategies are adequate. If the strategies are not adequate for small fires, then they would be definitely inadequate for larger fires.

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

Fire Scenario	Peak Fire size	Reference fire test
A	33.2 MW	Car fire test [8]
B	33.2 MW	Pool fire test in a tunnel [6]
C	35 MW	Coach fire test [9]

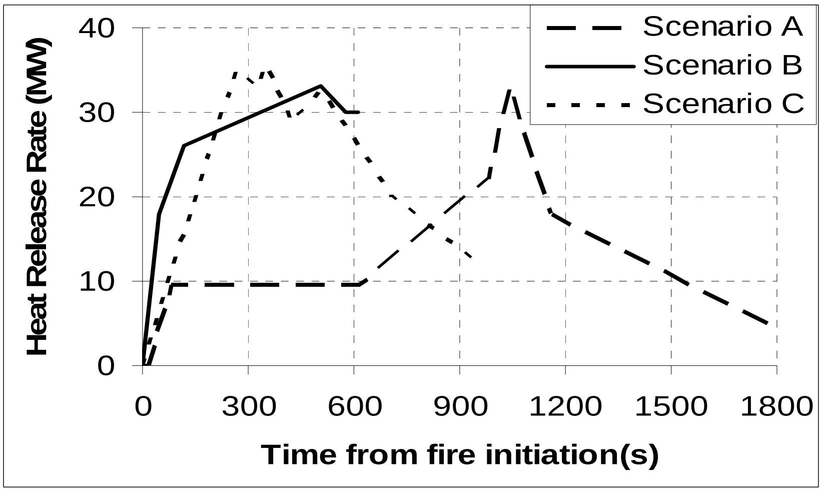

Fig.1. HRR profiles of design fires used in this paper (see Table 1 for details)

Scenario A is based on the HRR measured in a series of car fire tests [8]. The car was ignited with 1.5 L gasoline in an open tray under the left front seat. The left front window was completely open, and the right front window was half open. All the doors were closed. The HRR was measured using oxygen depletion technique by collecting all the fire products in a hood covering the burning car. For the present study, the originally measured peak HRR is scaled up from 8.3MW to 33.2MW 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 x 5.4 m wide x 120 m long tunnel under a 1.5 m/s wind speed [6]. The HRR in this test reached a peak value of 14.7 MW within 9 minutes of ignition, and a HRR per unit area of 4.15 MW/m^2 [6]. 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, 18m long, 2.8m wide and 3m high with 40 seats [9]. The HRR increases to 35MW within 5 minutes from ignition, and decreases quickly after 10 minutes from ignition.

The HRR profiles in Fig. 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. For the present study, the fire was assumed to have occurred at the centre 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 the life safety of the people in the tunnel, the Fire Dynamics Simulator (FDS) [7] was used to predict the smoke spread in the tunnel for scenarios A, B and C. The accuracy of FDS predictions was examined against the measurements of the temperature field and smoke backflow generated by a 2.5 MW pool fire in a ventilated tunnel [6]. FDS predictions of the temperature field and the smoke back-layering distance for this experiment were within ± 20% of the measurements. This exercise was conducted to calibrate FDS predictions for the present study, and then the model was used for predictions of smoke spread in scenarios A, B and C.

The computational domain was chosen to be 210 m long, as shown in Fig. 2. 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 200 m. The 200 m long domain covers the most critical section immediate upwind between the fire and the next exit 120 m away. Occupants from further upwind 120 m sections can evacuate more readily than those in the 120 m section next to the fire. The computational domain was limited to 200 m upwind of the fire, and not the entire tunnel length to save computational time. The domain also covers the entire tunnel cross-section and extends 0.5 m into the walls, ceiling and the floor. The ventilation rate was set at 2.5m/s as shown in Fig. 2. A fully developed flow boundary condition was given at the downstream end of the computational domain, where the smoke travelled in the same direction as the wind. Vehicles downwind of the fire are assumed to drive out of the tunnel safely, ahead of the smoke front.

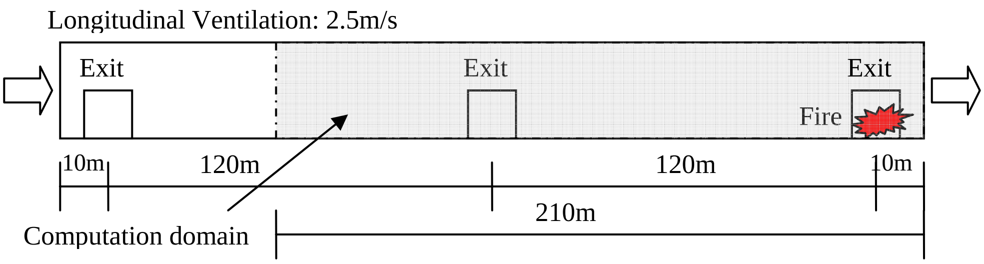

Fig.2. Schematic of computational domain (side view and not to scale)

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

To analyse the time-dependent development of untenable conditions upwind of the fire, the visibility and gas temperature at 2.1 m above the floor were calculated using FDS at 10 locations. These locations were at 0 m, 5 m, 10 m, 20 m, 40 m, 60 m, 80 m, 100 m, 120 m and 140 m upstream of the fire, along the longitudinal centreline of the tunnel.

A sensitivity study on the grid size was carried out, which indicated that a fine grid of 250 x 45 x 62 is necessary to get grid-size independent results. The grid size used for all the scenarios was as follows: (i) a fine grid of 20 cm x 16 cm x 16 cm, corresponding to tunnel length, width and height, respectively, in the region within 2 m from the fire, (ii) a coarse grid of 50 cm x 16 cm x 16 cm up to 75m upwind of the fire and 2m away downwind of the fire, and (iii) an even coarser grid of 120 cm x

16 cm x 16 cm for the region beyond 75 m from the fire. Time step length was adjusted so that the CFL condition [7] was satisfied. The time-averaged time step used in the present computation was 0.01s. To compute 600s 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 3 shows the predicted smoke backflow at 180 s and 300 s from the start of a fire for scenarios A, B and C. Clearly, the rate of rise of the HRR (Fig. 1) has a significant impact on the smoke backflow predictions. 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, 150 m and 130 m from the fire for scenarios A, B and C, 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.

Figure 4 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 in Scenario A than in 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 in Scenario A; whereas it takes only about 1 min in both Scenarios B and C. At 140 m upstream of the fire, it takes 18 min and 20 s for the visibility to drop to 25 m in Scenario A, whereas, it takes only 5 min and 15 s in Scenarios B and C.

According to the fire safety engineering standards [11, 12], occupants are disorientated and have difficulties in making decisions on what directions to take to escape if the visibility drops below 10 m. In the present analysis, the 10-m visibility criterion is used to calculate the tenable time, also called the Available Safe Egress Time (ASET) [11].

Figure 5 shows the 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 to 20 min are available for the people to evacuate, depending on the specific locations they are in. In Scenario B, less than one min is available for evacuation for those who are within the first 5 m upwind of the fire and 2 to 5 min are available for those located 20 m to 140 m upwind the fire. In Scenario C, only 50 s is available for people who are located within 5m upwind of the fire, and 3 to 6 min are available for those who are located beyond 20 m upwind of the fire.

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

Fig. 3. 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)

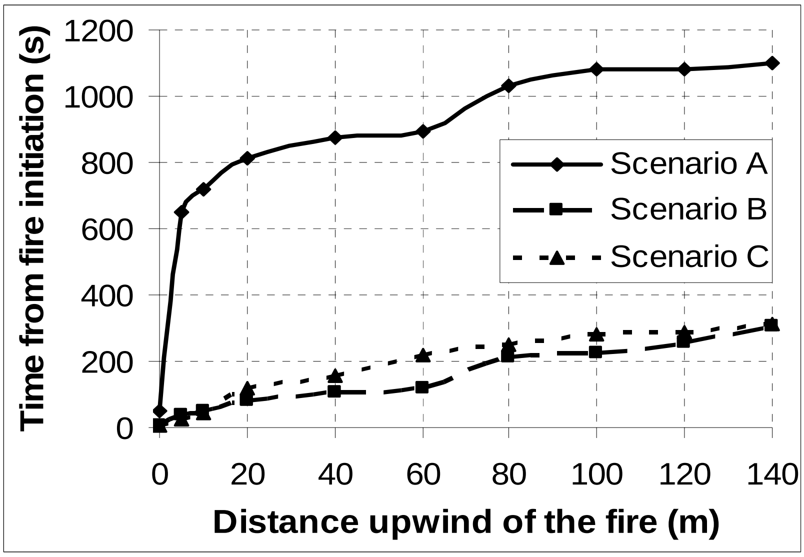

Fig. 4. Comparison of predicted time when visibility drops to 25 m for Scenarios A, B and C

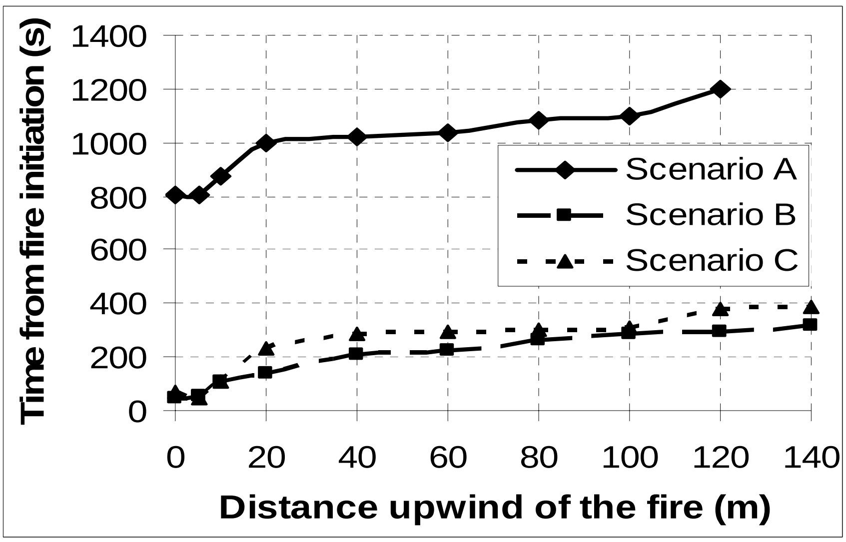

Fig. 5. Comparison of ASET [time when visibility drops to 10 m] for scenarios A, B and C

OCCUPANT EVACUATION

Occupant safety depends on whether the occupants can evacuate safely before the Available Safe Egress Time (ASET). The time required to egress is called Required Safe Egress Time (RSET). In the present analysis, the RSET is assumed to consist of 3 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, 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 people remote from the fire become aware of the fire.

In the present analyis, it is assumed that occupants are alerted when the smoke visibility above their heads drops to below 25 m, thus providing the visibility cue. However, if 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 alarms signals, car radio communications, vehicles being stationary or evacuating people moving away from the fire. In this instance, the maximum cue time is assumed to be 300 seconds, as a reasonably optimistic approximation.

Response time

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 [13] are shown in Table 2, where,
W1: live instructions using a voice communication system from a control room with closed circuit television facility, or live instructions in conjunction with well-trained, uniformed staff that can be seen and heard by all occupants.
W2: non-instructive voice message (pre-recorded) and/or informative warning visual displays with trained staff
W3: warning system using fire alarm signal and staff with no relevant training.

Table 2. Estimated delay time to start evacuation in min

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

Without detailed knowledge of the human behaviour in tunnels, people's reluctance to leave their belonging (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, if we take 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 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, 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 0.8m/s was 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 Figs. 7, 8 and 9, respectively. ASET is calculated from the FDS predictions of smoke backflow, and the time for untenable conditions, whereas RSET is calculated from a summation of cue, response and travel times.

It can be observed that the occupants considered in Scenario A have plenty of time to evacuate from the incident tunnel before untenable conditions occur, because RSET<<ASET. However, in Scenarios B and C, RSET >>ASET, therefore, untenable conditions arise rapidly and most people will be evacuating through smoky conditions.

According to Fig. 7, only those who are close to the accident will be influenced in Scenario A, as the available safe evacuation time (ASET) is longer than the required safe evacuation time (RSET). However, Figs. 8 and 9 show that ASET values are all shorter than RSET values in Scenarios B and C, all of the 100 people in the 120 m section adjacent to the fire will be at risk under the conditions discussed in this paper.

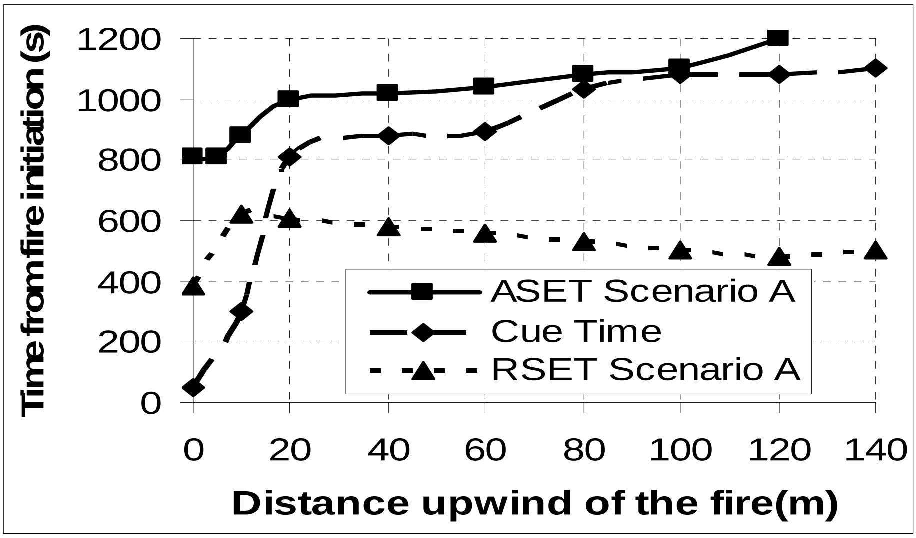

Fig. 7. Scenario A: ASET vs RSET Analysis

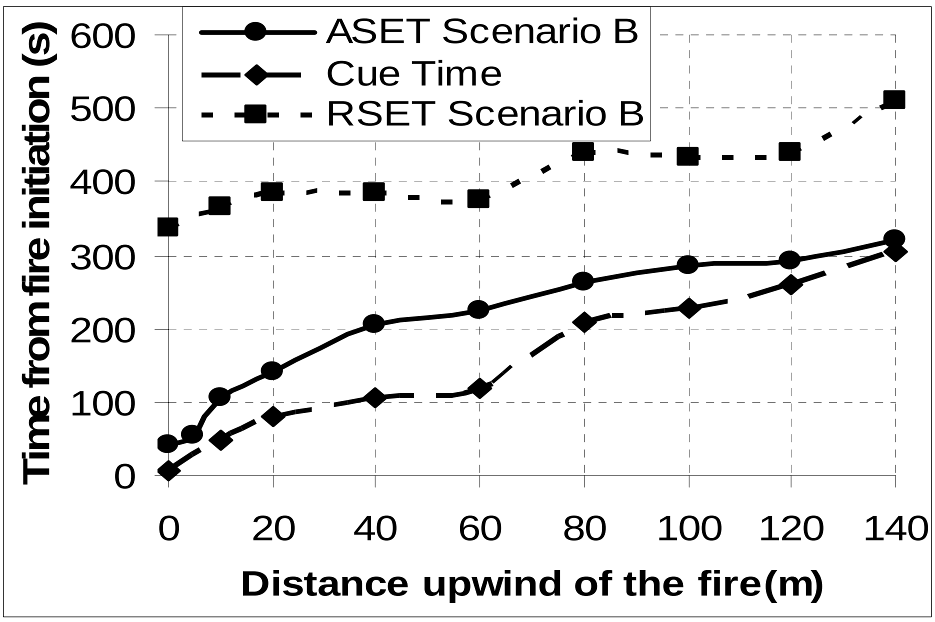

Fig. 8. Scenario B: ASET vs RSET Analysis

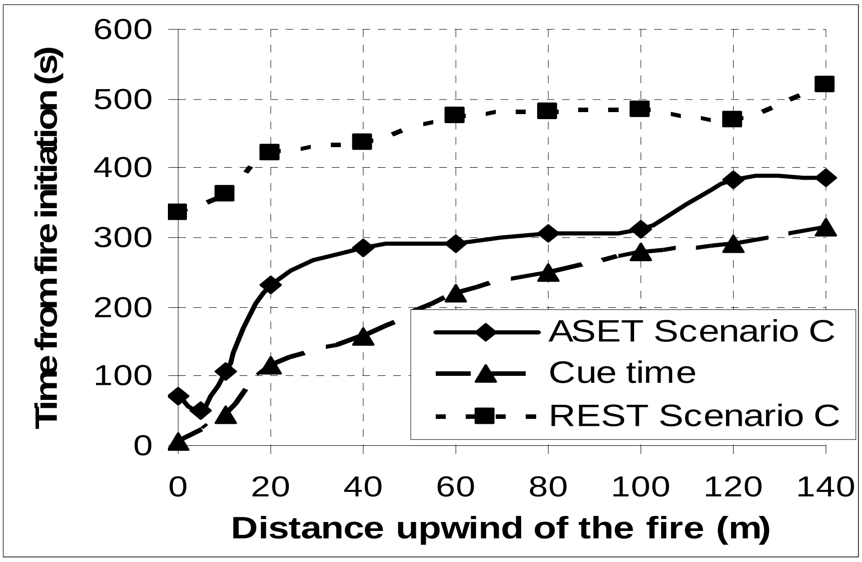

Fig. 9. Scenario C: ASET vs RSET Analysis

FIRE SUPPRESSION RELIABILITY AND RISK ASSESSMENT

The previous section shows that for scenarios such as B and C, the people in the immediate upstream section of the fire will not have sufficient time to evacuate and will be at risk of losing their lives. The first 120 m between exits, as shown previously, has about 100 people. Just using this section, one single accident involving a moderate fire will result with an expected death of at least 100 people. In this analysis, we have not considered the people beyond 140 m upwind of the fire.

According to fire statistics [1], about 5.7 fire accidents occur in road tunnels per 100 million driven km. The average number of vehicles passing through the Sydney Harbour Tunnel in 2002 was 87,529 per day [14], 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 driven km per year is 73.5 million. Based on 5.7 fires per 100 million driven km in a tunnel, the expected number of fires is 4.2. Assuming these fires are mainly those represented by Scenarios A, B, and C and that all these scenarios occur with equal frequency, then 2/3 of the fires can be fatal fires. Considering only those people in the immediate 120 m upstream section to the fire are at risk, the expected number of deaths per year is 4.2 x (2/3) x100 = 280. If the tunnel is longer, or the fire is larger, the expected number of deaths increases proportionally. It should be emphasised that the number of fatalities estimated are 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 the suppression system is installed and is 100% reliable and effective, no fire can develop into a major fire and therefore will not pose a risk. However, if the fire suppression is only 80% reliable and effective in controlling the fires, 20% of the fires would still develop into fires that can pose risk to people’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.

SUMMARY

This paper presents a methodology and a preliminary analysis to evaluate life safety in a transportation tunnel in the event of a fire accident. A typical road tunnel was examined under realistic fire scenarios using CFD modelling, egress modelling 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 people to react and escape safely. Safe egress of people is possible when the fire development is slow, as was shown in a scenario with a slow growing fire. For fast growing fires, an effective fire suppression system is vital in allowing the people to escape safely. A quick and reliable fire suppression system can control the fire and allow the people to egress to safety. Without a rapid and reliable fire suppression system, there could be serious life safety issues for tunnel users under the situation presented in this paper.

The present analysis was based on some simple fire and egress scenarios. Further research is needed to allow a more definitive analysis of fire safety in tunnels. This would include better-defined design fires and occupant behaviour for tunnel fire safety analysis. Research should also include development of fast and reliable suppression systems, and/or smoke control systems, that could be used to control fast growing fires in tunnels.

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NOMENCLATURE

ASET = Available Safe Evacuation Time
CFD = Computational Fluid Dynamics
FDS = Fire Dynamics Simulator
HRR = Heat Release Rate (MW or kW)
RSET = Required Safe Evacuation Time

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