Performance-Based Design Using Tunnel Fire Suppression

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ABSTRACT: This article reports on a quantitative risk assessment, supported by Computational Fluid Dynamics calculations, to compare the fire risk levels of two design options for the Yas Island Southern Crossing Tunnel in Abu Dhabi: a 5-cell tunnel with two escape galleries, compared to a 3-cell solution with no escape galleries, but with a fire suppression system installed in the highway cells. The risk levels for the two designs were shown to be broadly similar, and the 3-cell design was accepted as meeting the required level of fire safety by Abu Dhabi Civil Defence. The 3-cell tunnel benefited from a reduced construction cost compared to the conventional 5-cell design, as well as reduced risks to meeting the target date for construction completion.

INTRODUCTION

Fire safety is a key issue that can influence the configuration, structural design, mechanical/electrical/traffic control systems and the operation and management of tunnels. Recent high-profile fires in tunnels include the three fires in the Channel Tunnel between the UK and France (in 1996, 2006 and 2008), and the Burnley tunnel fire in Melbourne, Australia (2007), which was successfully controlled with a deluge system. On mainland Europe in the previous decade, there have been road tunnel fires with multiple fatalities at Mont Blanc (1999), Tauern (1999) and Gotthard (2001).

A number of guidelines, design standards and statutory instruments have been written or updated as a result of these fires, including NFPA 502 “Standard for Road Tunnels, Bridges, and other Limited Access Highways - 2008 Edition”, the European Union’s Directive 2004/54/EC on “Minimum Safety Requirements for Tunnels in the Trans-European Road Network”, and the World Road Association’s report on “Road Tunnels: An Assessment of Fixed Fire Fighting Systems” (2008). These standards allow a certain degree of flexibility in defining performance-based alternatives to standard prescriptive measures, as long as engineering analysis can demonstrate that an equivalent level of fire safety is maintained. The analysis usually takes the form of a qualitative and/or quantitative risk assessment, as recommended for example by BS 7974:2001 “Application of fire safety engineering principles to the design of buildings - code of practice”.

The risk assessment process normally comprises hazard identification, scenario development, consequence analysis, probability assessment and risk reduction (Figure 1). The ideal outcome of the risk assessment is a design that is agreeable to all stakeholders, including the Authority Having Jurisdiction. In the authors’ experience, this is best achieved by obtaining agreement at an early stage on the methodology of the risk assessment, as well as the primary data and assumptions that are fed into that assessment.

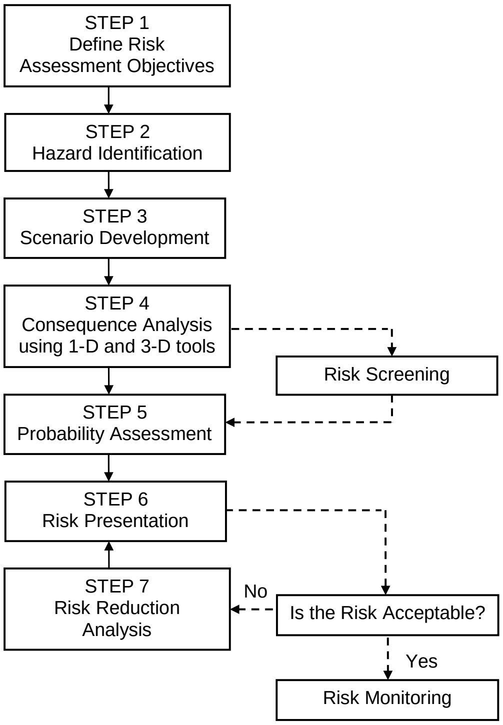

Figure 1: Basic fire safety engineering process (adapted from Barry, 1995)

PROJECT OVERVIEW

The Southern Tunnel links Yas Island with the mainland of Abu Dhabi, allowing access for public and private vehicles to the hotels, residential and commercial areas on the island (Figure 2 and Figure 3). The tunnel is 698m long, and therefore under the NFPA 502 standard has a category C rating. This determines the minimum level of fire protection equipment the tunnel must have. However, the fire safety specifications for the tunnel also call for consistency with the requirements of the United Kingdom's Design Manual for Roads and Bridges (BD78/99), which require a maximum distance of 100m between escape doors in the tunnel. For comparison, NFPA 502 prescribes a maximum distance between exits of 300m.

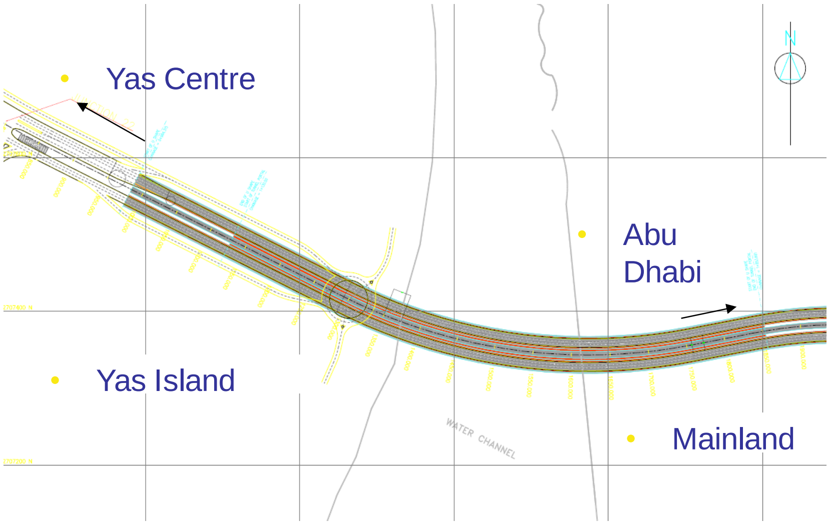

Figure 2: Horizontal Alignment of Yas Island Southern Crossing Tunnel

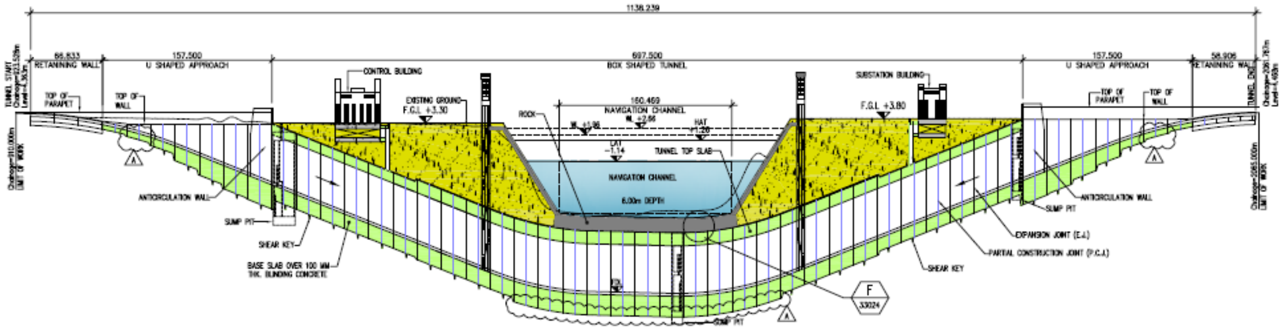

Figure 3: Vertical Alignment of the Yas Island Southern Crossing Tunnel

During the initial stages of the conceptual design, the tunnel was conceived as a five-cell structure, as per Figure 4. This comprised two 3-lane highway cells, a central Light Rail Transit (LRT) cell, and two emergency escape galleries on either side of the LRT cell.

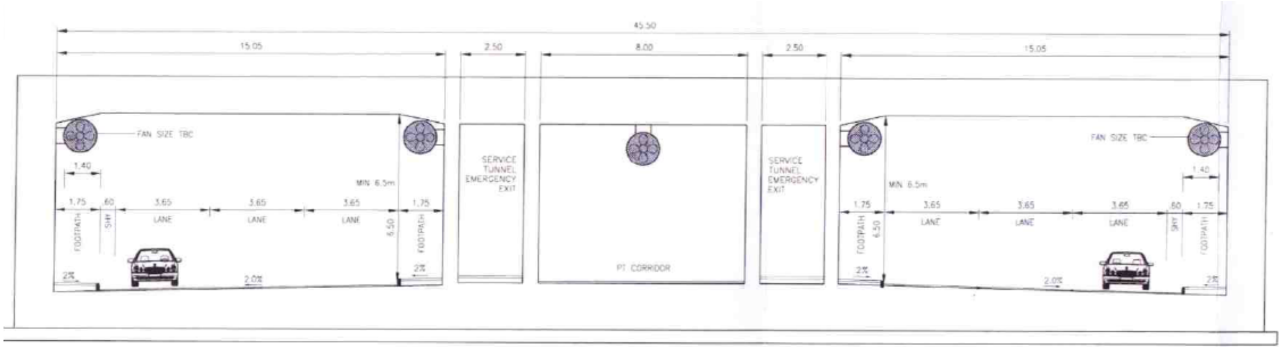

Figure 4: Original 5-Cell Tunnel Cross-Section (Concept)

In order to minimise the project construction costs, and to keep to the demanding construction programme, an alternative 3-cell concept (Figure 5) was proposed. This involved installing a low pressure deluge fire suppression system in the two highway cells to mitigate the risks of fire, and the construction of exits on both sides of the creek, which kept the maximum escape distances down to 294m (Figure 6 and Figure 7).

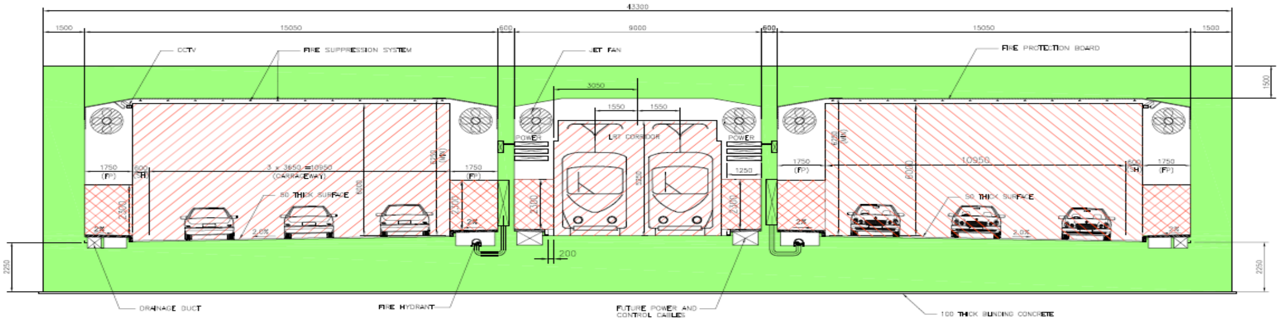

Figure 5: 3-Cell Tunnel Cross-Section

Although the 3-cell design conformed to the 300m maximum exit distance requirement of NFPA 502, it did not satisfy the more stringent 100m maximum exit distance of BD78/99. It was therefore decided to undertake a quantitative risk assessment to ascertain whether the overall fire risks of the 3-cell option were comparable to those of the 5-cell concept.

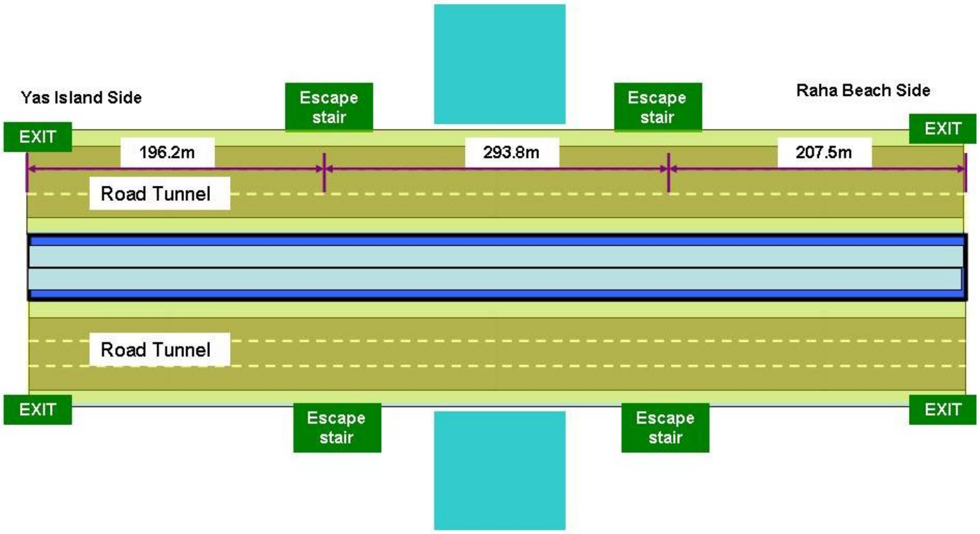

Figure 6: Escape Distances in 3-Cell Tunnel

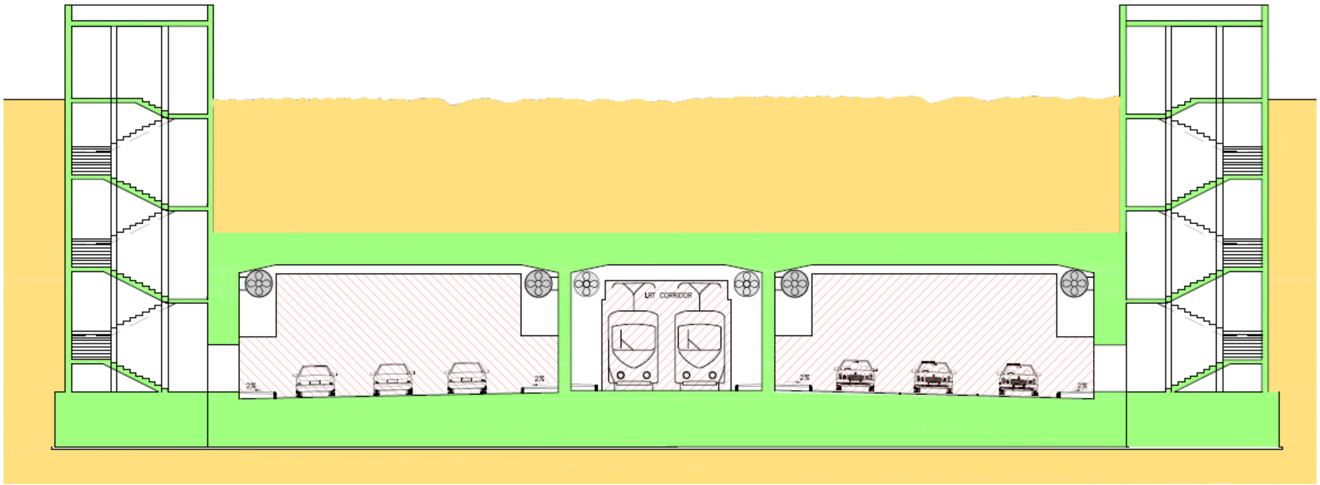

Figure 7: 3-Cell Tunnel Cross-Section at Location of Emergency Exits

EVACUATION ROUTES

A longitudinal ventilation system with jetfans was designed for the highway cells. In normal (non-congested) traffic scenarios, traffic downstream of any fire will be able to drive out of the tunnel, while traffic that is stuck behind a fire incident will be located in fresh air. A traffic management system ensures that priority is given to tunnel traffic in case of an incident, to reduce the likelihood of congested traffic in the tunnel. Once an incident has been confirmed, the traffic lights at entry to the affected tunnel will be switched to red and the traffic barriers will be lowered, in order to reduce the number of vehicles entering the tunnel.

Civil Defence will, in principle, be able to access the tunnel from both portals, since bi-directional jetfans will be specified. At the initial (evacuation) stages, the airflow direction will be the same as the traffic direction. The airflow direction can be reversed by Civil Defence if required, to enable them access to the source of fire from the opposite direction.

FIRE RISK ASSESSMENT

Fire Size

The maximum heat release rate for a design fire within the Yas Island Southern Crossing Tunnel is determined by the type of vehicles permitted in the tunnel. Petrol tankers and other dangerous goods vehicles are banned from using this tunnel, but there are no restrictions on heavy goods vehicles, hence it was considered that a maximum design fire heat release rate of 150MW should be assumed for the tunnel design (Opstad, 2005). The access for flammable good vehicles is to be via the Shahama – Saadiyat freeway.

There is experimental evidence that fire heat release rates are substantially reduced by fixed fire suppression systems. From a review of experimental evidence, a design fire heat release rate of 30 MW is considered appropriate for the 3-cell option if a fixed fire suppression system were installed in the Yas Island Southern Crossing Tunnel. Therefore assumed maximum fire heat release rates for this project were:

3 Cell Option:	30 MW (HGV) – with fire suppression
5 Cell Option:	150 MW (HGV) – without fire suppression
Car Fire:	4 MW – with fire suppression
Car Fire:	8MW – without fire suppression

Evacuation Scenarios

Evacuation scenarios under both congested and non-congested traffic conditions were considered. For the purposes of our risk analysis, it has conservatively been assumed that there will be congestion downstream of an accident in 12.5% of incidents (and hence that there is no traffic congestion in 87.5% of incidents). This corresponds to expected periods of congestion for 1.5 hours in the morning and evening peak periods. The likelihood of congestion downstream is minimized since the traffic plans will allow for priority to tunnel traffic in an emergency. The provision of the 3-cell option will only differ from that of the 5-cell option in the length of time required to evacuate the tunnel, due to the increase in distance and the environment in which people will have to evacuate in the 3-cell option.

(a) No Congestion Downstream

In the scenario where there is no congestion downstream of the fire, vehicles in front of the incident may continue to drive out. Therefore, smoke can be ventilated downstream, as there will be no people evacuating their vehicles in this area. The visibility will be reduced downstream of the incident for both the 3 and 5 cell options, but this should not normally increase the risk to the motorists driving out of the tunnel.

Drivers evacuating upstream of the fire can be expected to be located in a fresh air environment, since the piston effect of moving vehicles and the thrust of the jet fans should help drive the smoke downstream. Therefore, although the 3-cell option involves an additional distance to a place of safety, there are no strict time limits on the time required for evacuation to a place of safety.

(b) Congestion Downstream

In the scenario where there is traffic congestion downstream of the fire, vehicles in front of the incident will not be able to drive out. All drivers will therefore need to leave their cars and evacuate to the nearest exit point. Drivers upstream of the fire will be in a similar situation to the non-congested scenario and therefore have no immediate limits on their evacuation time due to the conditions.

For the first few minutes of the evacuation time, any fire suppression system will not be active. Therefore until the incident has been detected, confirmed and the delay time of the fire suppression system exceeded, the only difference between the 3 and 5 cell options is the distance required to exit the tunnel. After this time, the fire suppression and longitudinal ventilation systems are activated (not necessarily simultaneously). The fire suppression system reduces fire growth, lowering temperatures in the tunnel and reducing the risk of fire spread.

Timelines

A typical fire scenario in the Yas Island Southern Crossing Tunnel is described below and has been assumed as part of quantitative risk model [with times in parenthesis]:

1. Fire breaks out in a vehicle [T=0 s]
2. The fire is detected by the tunnel operators via the CCTV-based Automatic Incident Detection system [$T = t_1$]
3. A decision is made by the tunnel operators to order a full evacuation of the tunnel [$T = t_1 + t_2$]
4. The tunnel operators stop the traffic and instruct motorists to leave their vehicles and evacuate the tunnel [$T = t_1+t_2+t_3$]
5. The fire suppression system is activated 3 minutes (NFPA 502) after the instructions to evacuate the tunnel are given.
6. The motorists make a decision to abandon their vehicles and start to evacuate [$T = t_1+t_2+t_3+t_4$]
7. Motorists walk to the points of safety (portals and evacuation shafts), until the tunnel is empty of all people [$T = t_1+t_2+t_3+t_4+t_5$]

Table 1 indicates a likely range of overall evacuation times for the 5 and 3 cell options, with the maximum time taken assuming the fire is blocking an exit.

Variable	Meaning	Assumed value
t_1	Detection time	1 to 2 minutes from fire growth (1 to 5 minutes from start of incident)
t_2	Operator or automatic decision time	1 to 2 minutes
	Stop traffic	1 to 2 minutes
t_3	Instruction time	1 to 2 minutes
t_4	Motorists' decision time	1 to 2 minutes
	Fire suppression activated	3 minutes after instructions to evacuate are given
t_5	Walking time	Distance / 38m/min
	Total time to empty cell	8 – 13 min (5-cell option) 11 – 16 min (3-cell option)

Table 1: Breakdown of evacuation procedure times

For an HGV fire with fire suppression, the effective fire size is limited to 30MW since the fire suppression is assumed to be activated 8 minutes after the start of the incident. Without fire suppression the fire is assumed to grow to 129MW after 25 minutes, based on a 'fast' growth rate as per PD 7974-1 (British Standards Institution, 2003).

The evacuation timeline has been represented as a fault tree using PrecisionTree software, based on the fire growth rate assumptions for the suppressed and unsuppressed fires. Fires directly in front of an exit (full evacuation distance) and those between exits (half evacuation distance) have been included in the quantitative risk analysis. The probability of the incident blocking an exit has been predicted using various fire sizes and therefore changes with the incidents.

Consequence Analysis

Table 2 shows estimates of the fatalities resulting from different fire types. As a result of the higher evacuation times, the consequences of a severe or catastrophic fire are worse for the 3-cell option than the 5-cell option. However, very severe and catastrophic fires can only occur if the fire suppression system fails during a HGV fire. The probability of these two events occurring simultaneously is very low. The fault tree in Appendix A assumes 1% of incidents result in an HGV fire and that the fire suppression system is unavailable (either due to maintenance or failure) for 1.8 days per year. Based on these assumptions, such circumstances could be expected to occur in approximately 1 out of every 20,000 incidents.

Fatality Rates	**5 Cell Option**	**3 Cell Option**
Damage Only (up to 5MW) - Car Fires	0	0
Minor Fire (up to 10MW and 30min burning time) - Car Fires	0	0
Severe Fire (up to 50MW) - Car Fires	1	2.5
Very Severe Fire (up to 100MW) - Goods Vehicle Fires	3	7.5
Catastrophic Fire (greater than 100MW) - Goods Vehicle Fires	20	50

Table 2 Estimated fatalities resulting from different fire types

Monte Carlo Simulations

In order to ascertain the overall fire risk profile of the two tunnel options, Monte Carlo simulations were undertaken of a range of fire scenarios, with each scenario being defined by 17 parameters that are allowed to vary within Gaussian distributions, each with a defined mean value and standard deviation. A typical result of these calculations is shown in Figure 8. While car fires define the highest frequency / low consequence fires, HGV fires correspond to low frequency / high consequence events. Fire suppression is seen to shift the 'secondary peak' of the frequency/consequence diagram towards lower consequences in terms of fatalities, almost by an order of magnitude. It is seen that the 3-cell option with fire suppression provides a similar risk profile to that of the 5-cell option without fire suppression.

In practice, there will be a range of light goods vehicles (LGVs) that have an intermediate heat release rate and accident probability between those of passenger vehicles and HGVs. Such vehicles have not been included in the present analysis. However, the authors consider that the conclusions of the study remain valid.

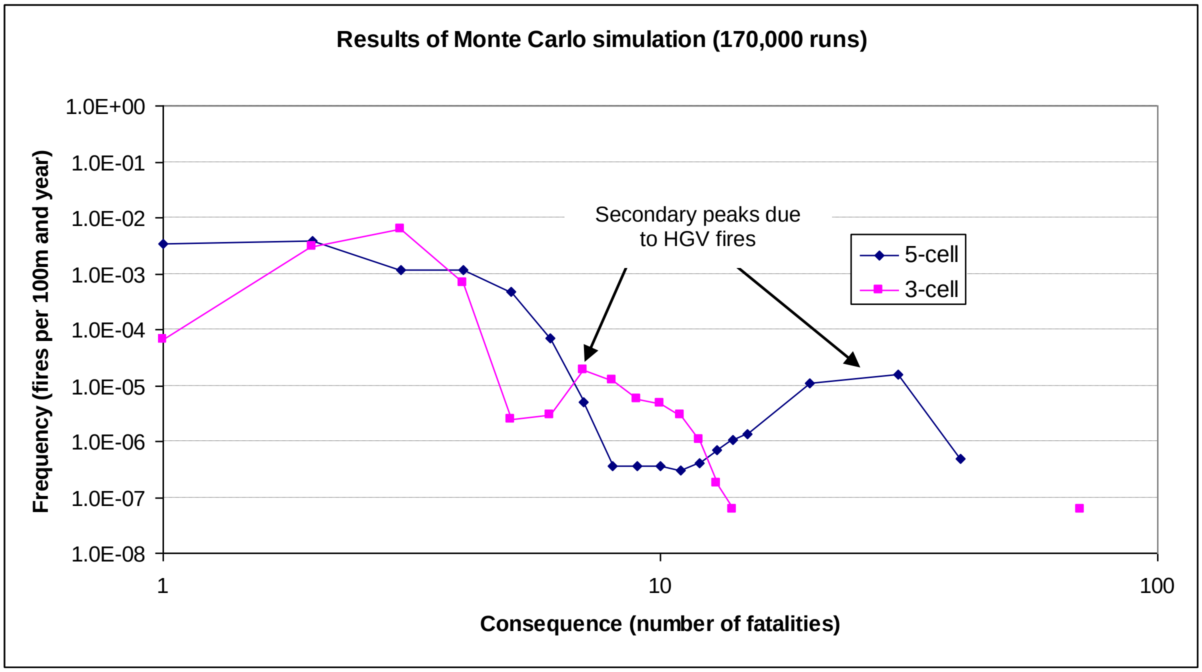

Figure 8: Frequency/Consequence Diagram for 3- and 5-Cell Tunnel Options

Results of Quantitative Risk Assessment

Although the 3-cell option increases the distance between exits and therefore the evacuation time for motorists, installation of a fire suppression system is likely to reduce the overall life safety risk to that of a 5-cell option, which has escape accesses every 100m along the tunnel.

If the fire suppression system should fail, the fire may grow to a size where the jet fans cannot fully ventilate the tunnel, as the system has been designed assuming a maximum of a 30MW fire. The probability of this situation occurring is very low (approximately 1 out of every 20,000 incidents), as indicated by the quantitative risk assessment described above.

The only other scenario where the 3 cell and 5 cell options differ significantly is that of a heavy goods vehicle fire in the presence of congested traffic (due to the higher evacuation times for the 3-cell option). Since such circumstances will only account for a small proportion of incidents any increase in fatality rates is likely to be marginal.

Two parameters within the risk assessment significantly affect these results: the pre-movement time (i.e. the time elapsed prior to the movement of motorists towards points of safety) and the time during which the fire suppression system is unavailable (either due to planned maintenance or failure). Hence, the installation of public address systems to encourage motorists to leave their vehicles and evacuate the tunnel in an emergency, and rigorous standards for maintenance and reliability of the chosen fire suppression system are required.

COMPUTATIONAL FLUID DYNAMICS (CFD) CALCULATIONS

In order to provide a better insight into the safety consequences of the 3-cell and 5-cell designs, a number of CFD calculations were undertaken for fire scenarios with 150MW heat release rate (unsuppressed HGV fire for 5-cell design) and 30MW heat release rate (suppressed HGV fire for 3-cell design). The calculations were undertaken using the Fire Dynamics Simulator (FDS) software from National Institute of Standards and Technology.

For the proposed sprinklered tunnel, the worst credible fire scenario is a HGV fire within the central portion of the road tunnel. Based on NFPA 502, World Road Association and experimental data, this has been modelled as a fast growth rate 30MW fire. This was defined as a prescribed t^2 fire growth curve and therefore the sprinklers will not be used to suppress the fire but will not cool the gas layer. This method of defining the fire is more conservative and will allow for the fact that shielding of a fire can occur.

For the non-sprinklered tunnel a fast growth 150MW fire will be used in the same location designed to simulate a large HGV fire with additional vehicle involvement .A 10m x 2m block the same size as a HGV was modelled in the tunnel with the prescribed fire applied to this object.

The reaction used in both these fires is cellulosic with a soot yield of 0.1g/g. The CO yield was set as 0.05mol/mol. These values were chosen to conservatively represent the type of fuel loads that would be present in a large HGV fire.

A steady airflow velocity of 2.3m/s imposed by the jetfans was assumed in the analysis for both the 30MW and 150MW fire scenarios.

Owing to the size and geometrical complexity of the tunnel, it is meshed with 0.5m x 0.5m x 0.5m grids throughout, giving a total cell count of 3.5 million. Grid sensitivity checks were carried out on the calculated air velocities in the tunnel with a range of grid sizes (Figure 9). These checks confirmed that the choice of the 0.5m mesh size was reasonable for the purposes of this analysis.

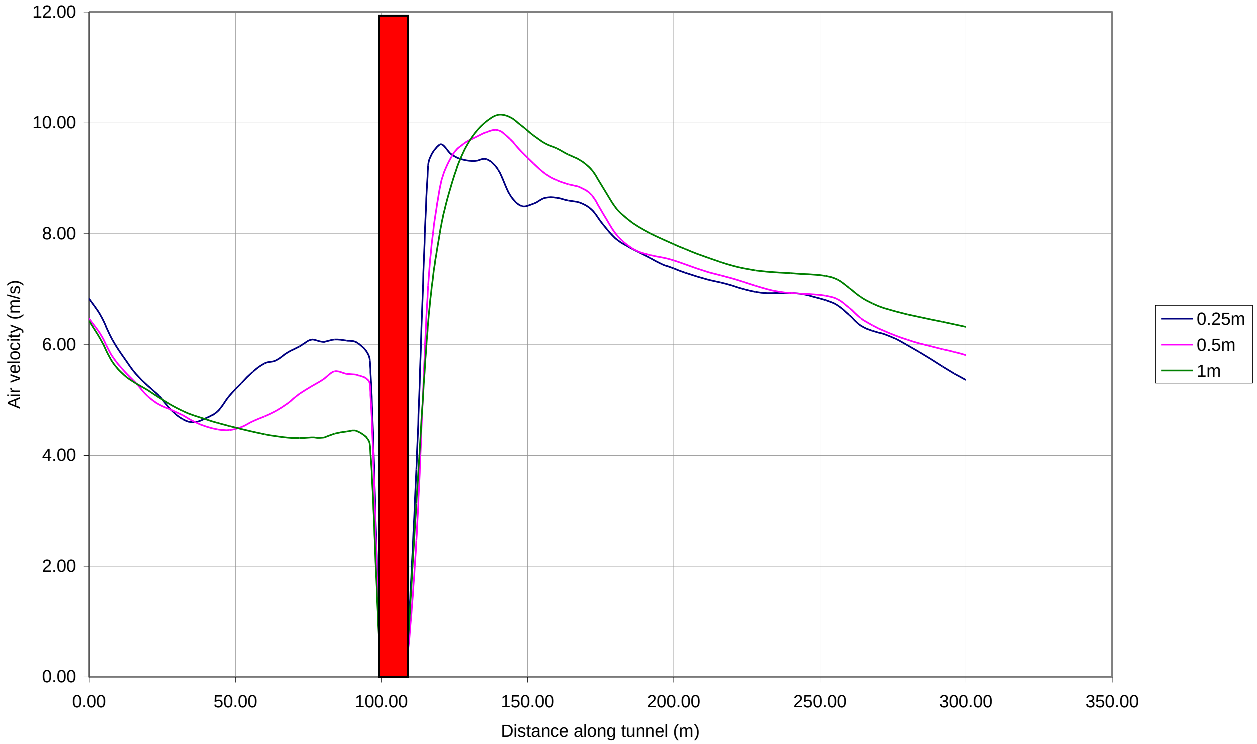

Figure 9: Graph showing the air velocity (m/s) for different meshes (red bar is fire location)

Figure 10: FDS Model of Yas Island Southern Crossing Tunnel (End View)

Figure 11 shows a graph of visibility for the 150MW fire scenario along the entire length of the tunnel at four minute intervals. Four minutes after the fire has started, visibility is better than 10m in all parts of the tunnel. After five minutes, visibility deteriorates below 10m, at a distance 50m downstream of the fire up to the tunnel exit. After 16 minutes the visibility is untenable at all points downstream of the fire. The upstream visibility distance is maintained at greater than 10m at all times.

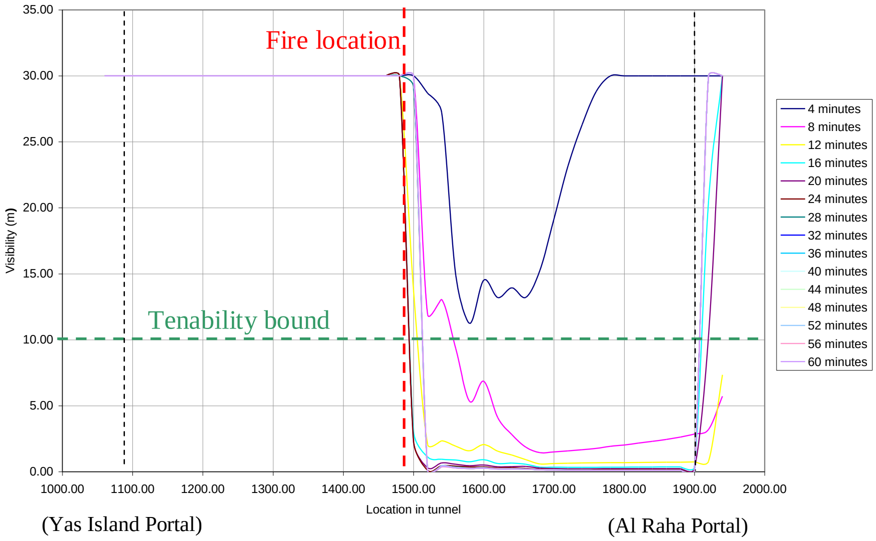

Figure 11: Visibility distances during the 150MW tunnel fire

Shown in Figure 12 is a graph of temperature along the entire length of the tunnel at four minute intervals. Conditions are tenable until 14 minutes after the fire has started. By 19 minutes, conditions have become untenable up to 220m downstream of the fire. At twenty three minutes the whole of the tunnel downstream of the fire has become untenable. Upstream of the fire, temperatures are maintained tenable at all times.

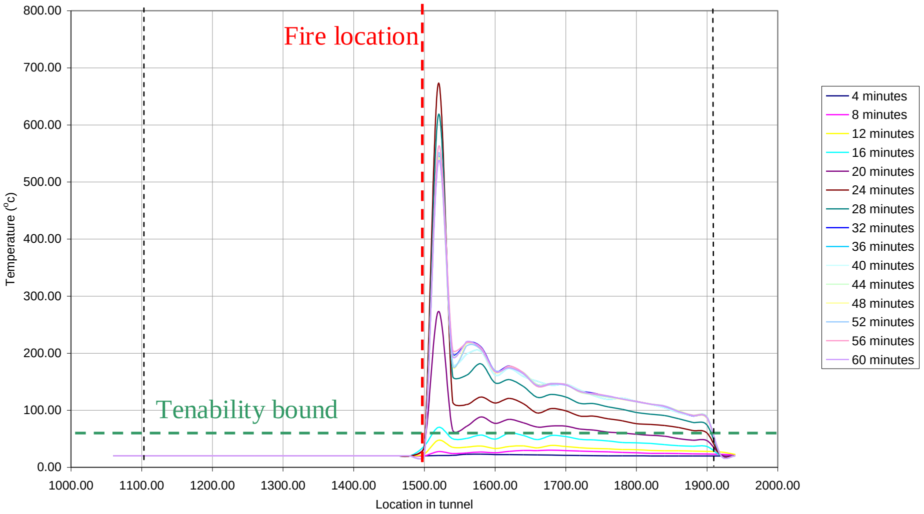

Figure 12: Temperatures during the 150MW tunnel fire

Figure 13 shows a graph of CO concentration during the tunnel fire. The levels of CO continue to rise until 32 minutes where steady state conditions are observed in all areas of the tunnel apart from immediately around the fire source. The peak level is 402ppm. Around the fire source levels continue to increase and after 60 minutes the level is 1150ppm.CO levels are not shown to increase upstream of the fire location.

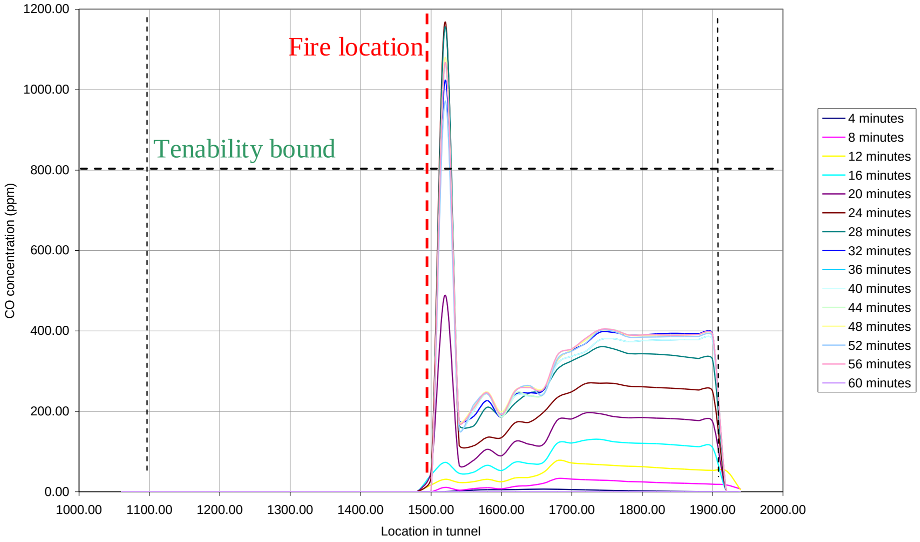

Figure 13: CO concentrations during the 150MW tunnel fire

Figure 14 shows the expected visibility distances for the 30MW fire scenario. Visibility is better than 10m, up to seven minutes after the fire has begun. After seven minutes, visibility conditions deteriorate in the tunnel. By 16 minutes, visibility is worse than 10m at all locations downstream of the fire.

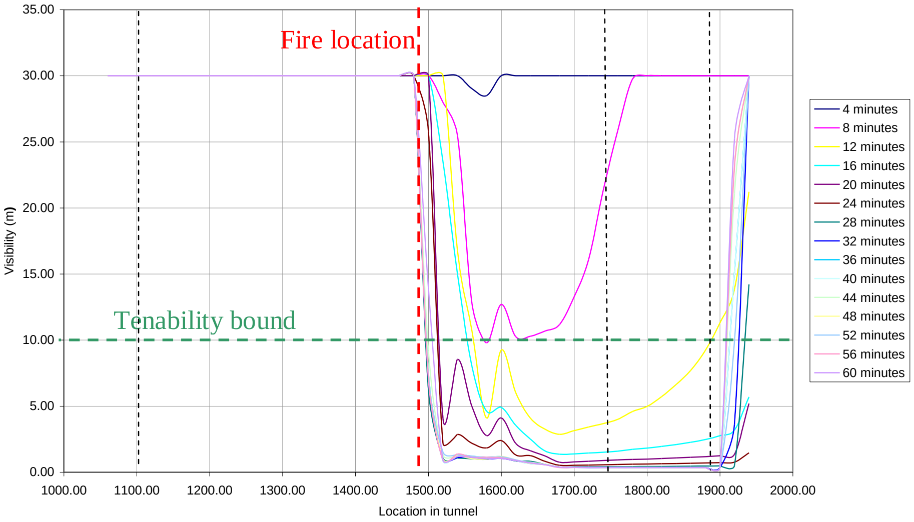

Figure 14: Visibility distances during the 30MW tunnel fire

Figure 15 shows the temperatures along the entire length of the tunnel at four minute intervals. The temperature is tenable in all parts of the tunnel up until twelve minutes. After this time conditions are tenable in all parts of the tunnel apart from a 30m section 50m downstream of the fire source. This remains the case for the rest of the simulation.

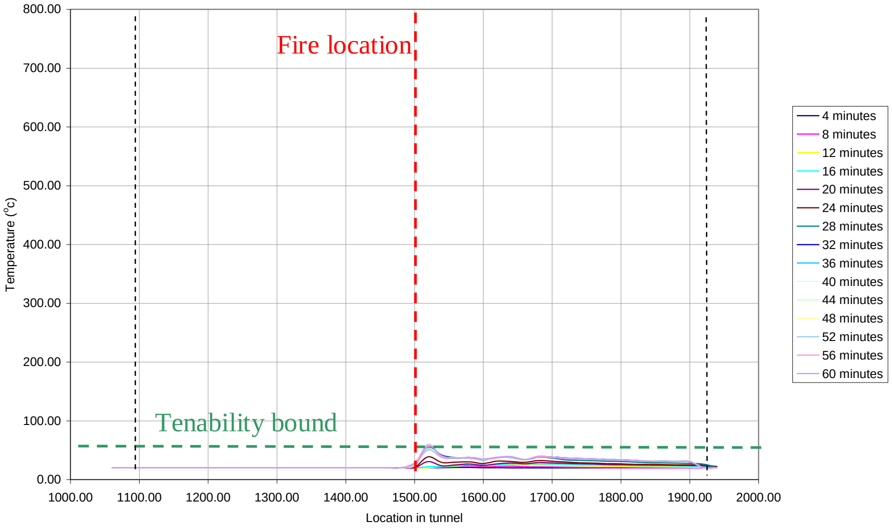

Figure 15: Temperatures during the 30MW tunnel fire

Figure 16 shows the CO concentration in ppm for the 30MW fire scenario. Upstream of the fire there is no increase in concentration. Downstream of the fire the levels increase until sixteen minutes where steady state conditions are observed. The highest concentration in any part of the tunnel is 102ppm, which is well within the tenability limit of 800ppm.

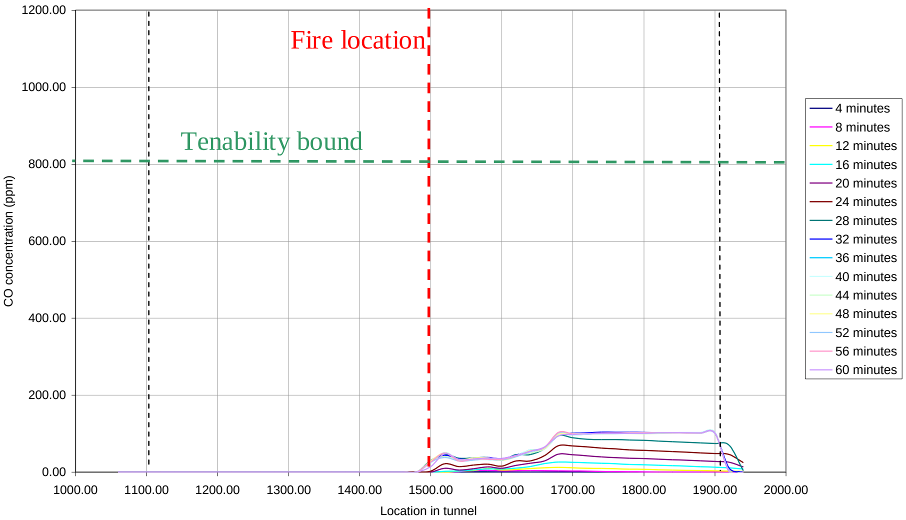

Figure 16: CO concentrations during the 30MW tunnel fire

In summary, the CFD calculations show that the longitudinal ventilation system with jet fans works well to maintain tenable conditions upstream for escape and for fire service access. It is also noted that a significant improvement in tenability conditions (temperature, CO) can be obtained downstream of an HGV fire due to fire suppression, although the visibility conditions are still expected to be poor.

CONCLUSIONS

On the basis of the quantitative risk assessment presented in this paper, the Yas Island Southern Crossing Tunnel was constructed as a 3-cell structure, with the agreement of the Abu Dhabi Civil Defence, and in time for the Formula 1 Grand Prix that was held in Abu Dhabi between 30 October and 1 Nov 2009. The 3-cell structure with fire suppression in the highway cells and with a maximum distance to exits of 293.8m was shown to have a similar risk level to a 5-cell structure with 100m between exits. The performance-based fire safety design of this tunnel thus provided significant construction and programme advantages to this project.

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