Emerging trends in tunnel fire suppression

Fire suppression is emerging as a key risk reduction measure for consideration in tunnels under construction or undergoing refurbishment. However, understanding the possible benefits, limitations and costs of fire suppression, and reflecting that understanding in the project decision-making process, is still a nascent science. This article describes some of the latest technical guidance available, and how it was applied to two tunnels in order to reduce societal costs related to fires, and to minimise construction costs and programmes.

Until relatively recently, the issue of tunnel fire suppression was considered very differently in various parts of the world. In Japan, fixed fire suppression systems are installed in tunnels with a length of 3,000m or longer, and which have a traffic volume of 4,000 vehicles per day or greater. The Australasian Fire Authorities Council's fire safety guidelines for road tunnels require installation of fire suppression systems in long road tunnels in Australia. However, European tunnel designs generally followed World Road Association (PIARC) guidelines, which did not support the principle of tunnel fire suppression prior to 2008. The same reticence with respect to tunnel fire suppression was evident prior to 2008 in the National Fire Protection Association (NFPA)'s standard 502, which is widely used in North America and elsewhere.

However, in 2008, both the World Road Association and NFPA published updated standards with respect to tunnel fire suppression, which acknowledged the positive benefit that such systems may bring to reducing the growth of tunnel fires, and also to prevent their spread. Neither of these updated standards advocates a blanket requirement for fire suppression to be installed in tunnels, though. The World Road Association recommends that a feasibility study, cost/benefit analysis and risk assessment is undertaken for any tunnel where fire suppression is under consideration. The NFPA recommends an engineering analysis to demonstrate the maintenance of safety levels where fire suppression systems may be

Dr. Fathi Tarada
Co-Chairman of the PIARC Working Group on Air Quality, Fire and Ventilation, and member of the Technical Advisory Committee for the International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels.

installed, as part of an integrated approach to the management of safety. In addition, the NFPA recommends that both the advantages and disadvantages of such systems have to be considered.

An example of a recent cost-benefit analysis to assess whether a fire suppression system should be fitted to a tunnel was undertaken for the New Tyne Crossing (NTC), a major project currently underway in Newcastle, UK. The project comprises construction of a second vehicle tunnel under the River Tyne in Newcastle, and the refurbishment of an existing tunnel, which is now over 40 years old. Permanent works for the new tunnel's construction commenced in October 2008 and are expected to be completed in February 2011. Once the new tunnel is in service, the existing tunnel tube will close for refurbishment until December 2011. By early 2012, both tubes are due to open to traffic and serve as a unidirectional flow tunnel.

A Tunnel Design and Safety Group (TDSCG) has been formed by the Tyne and Wear Integrated Transport Authority (TWITA) to advise on tunnel safety issues. In addition to a whole range of active and passive fire protection systems to be provided in the

tunnels, the TDSCG was considering whether a fixed fire suppression system should be installed. The current fire safety guidelines and standards in the UK have not recommended fixed fire suppression system to be installed in tunnels, and no fixed fire suppression system has been installed in any UK tunnel to date. Members of the TDSCG had diverse views on the provision of a fixed fire suppression system.

The author was commissioned as an independent expert to advise on whether the installation of a fire suppression system should be recommended. A quantitative risk assessment was developed to determine the likelihood and consequences of different severity of fire incidents occurring in the tunnels. Subsequently, a cost/benefit assessment of the provision of a fixed fire suppression system was conducted taking into account the cost of installation, the maintenance and repair costs and the likely financial benefits measured in terms of lives saved and savings in tunnel repair costs and traffic delay costs.

In order to estimate the frequency of fire events, historical data from the existing tunnel and other tunnels world-wide was obtained. Consequences were then assigned to events and monetary values assigned to reflect the direct costs of a fire incident, the associated cost of any casualties, the cost of any traffic delays and the cost of any repairs to the tunnel.

The quantitative cost-benefit assessment calculates the net benefit (Expected Net

Figure 1: New Tyne Crossing Route

Value) of a fixed fire suppression system based on a comparison of benefits and costs over an assessment period of 60 years. This assessment period is a compromise between the design life of the tunnel structure (120 years) and the typical life of a fire suppression system (15 to 20 years). Benefits are based on an assessed reduction in frequency and associated impact of tunnel fire incidents, and are reported over the assessment period.

Because of the variability in input data to the model, it is not appropriate to report the net benefit as a single figure, and a sensitivity analysis has been used to aid

The current fire safety guidelines and standards in the UK have not recommended fixed fire suppression system to be installed in tunnels, and no fixed fire suppression system has been installed in any UK tunnel to date

decision making by presenting benefits using a probabilistic approach.

Figure 2 shows a schematic diagram of the theoretical model structure.

A parametric sensitivity test forms an integral part of the risk assessment model and is carried out using a Monte Carlo simulation to model the likelihood of different fire events. A baseline model is then set up in which the cost associated with different levels of fire event are calculated for use as a reference point with which a comparison of the proposed fire suppression system will be made.

The benefits of the fire suppression system are considered to be a combination of reduction in:

▶ Personal injuries and fatalities
▶ Delay to road users
▶ Damage to tunnel structure

The model represents this by means of a reduction in the number of fires which progress from minor to severe, from severe to very severe and from very severe to catastrophic. However, assuming that a safety operational strategy would require that water discharge is delayed
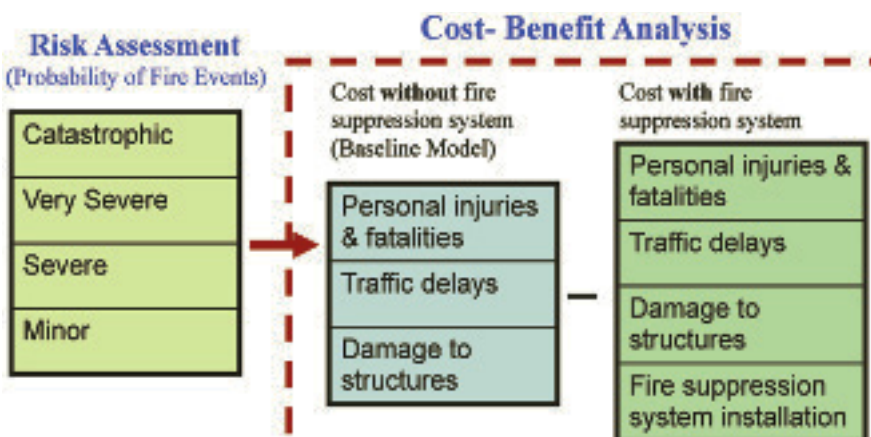

Figure 2: Theoretical Model Structure

until after evacuation, damage-only fires and the proportion of such fires that progress to become minor fires will not be reduced.

The benefits of fire suppression manifest themselves in the model as a reduction (compared to baseline) in the number of fires that progress from one level of severity to the next. Fire suppression was assumed to reduce both the cost of delay and damage and the cost of injury, with the former accounting for twice the saving of the latter. The main reasons for assuming a modest life safety benefit of fire suppression are:

1. A significant number of injuries and fatalities may be due to vehicle impacts rather than the actual effects of a fire

2. The delay in operating the fire suppression system, which is normally required to evacuate the tunnel prior to water discharge, may mitigate against saving lives and injuries. For example, tunnel fire suppression systems in Japan and Australia are not normally activated until after all road users have been evacuated (although there are exceptions to this, based on dynamic risk assessments – and Japanese standards now recommend discharging
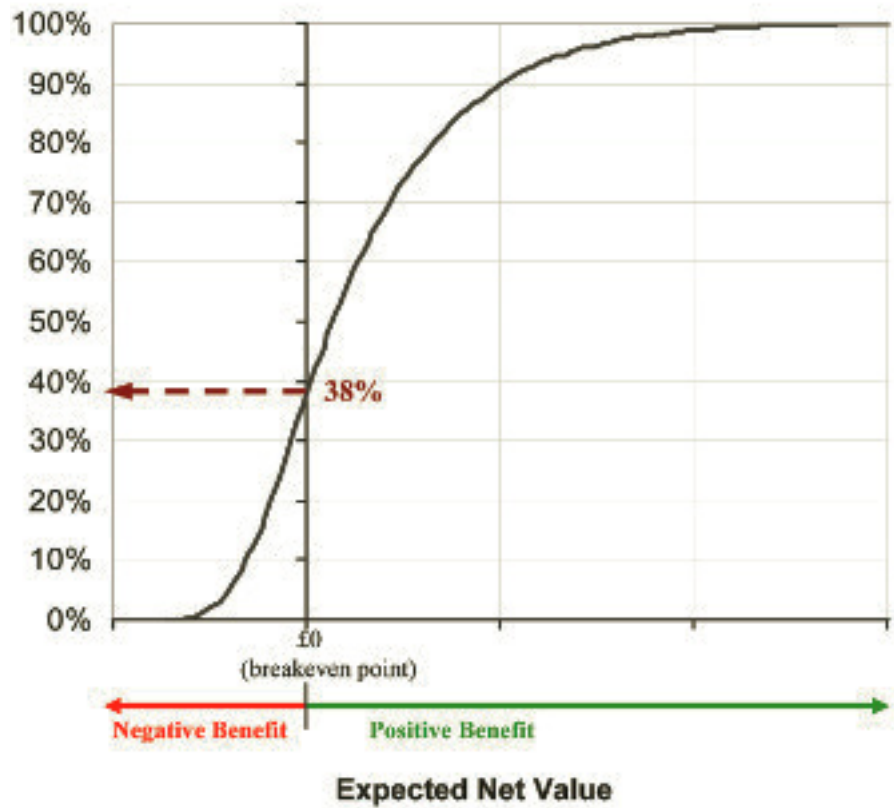

Figure 3: Expected Net Value of the Fixed Fire Suppression System

water three minutes after fire detection in uni-directional traffic and 10 minutes for the bi-directional case)

Where possible and appropriate, the economic principles adopted in the development of the
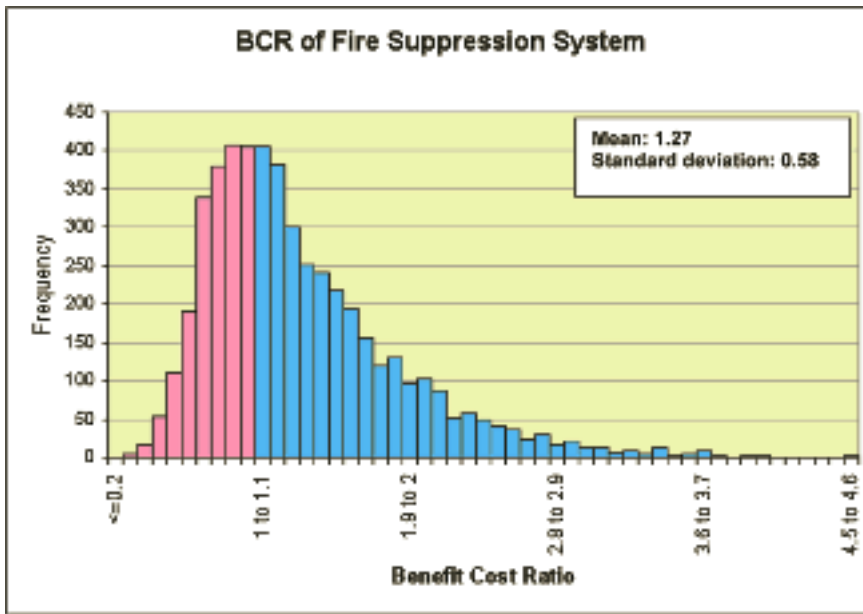
EYEVIS

Figure 4: Benefit-Cost Ratio for Fire Suppression System

quantitative model are aligned with the UK Highways Agency's published methodologies for cost benefit analyses (the COBA manual). Variation in some costs over future years was taken into account by increasing those costs in line with the forecast variation in GDP.

Given the limitations on available historical data, it has been necessary to derive the frequencies of different types of fire incidents in tunnels from a variety of sources and to exercise judgement when applying figures to the NTC.

COBA gives an assumed decrease in accident rates over time for the surface road system. The cost-benefit assessment adopted a similar rate of decrease applies to all fire incidents within the tunnel.

The Monte Carlo simulation generates a set of input parameters for the model from a specified range of possible parameters. This is done a large number of times (over 5000 runs), generating a smooth and consistent profile of probable outcomes from the model.

The decision to install a fire suppression system on the basis of a benefit-to-cost ratio (BCR) above unity may be controversial, since most of the benefits accrue from the reductions in traffic delays, rather than life safety benefits

The results of the Monte Carlo stimulation show a broad spread of the Expected Net Value curve with a positive mean benefit, even though there is a possibility that the system would not provide a net benefit. For an assessment period of 60 years, there is approximately a 38% chance of a negative benefit. In other words, the probability of a tunnel fire suppression system providing a net positive benefit to society is 62%.

For the net benefit gained, the key types of fire incident that the model predicts significant cost saving are:
▶ 42% are due to severe fires
▶ 29% are due to very severe fires
▶ 28% are due to catastrophic fires

The key types of costs where the model predicts significant benefits are:
▶ Mean reduction in traffic delays due to tunnel closure: 71%
▶ Mean reduction in injuries, fatalities and emergency service attendance costs: 18%
▶ Mean reduction in damage to tunnel: 11%

As far as the Benefit Cost Ratio (BCR) is concerned, the fire suppression system has an average BCR of 1.27. The result indicates that for every pound sterling of investment, the fire suppression system is likely to bring 1.27 pounds of economic benefits to the society. The BCR levels equal to or over than 1 are shown as blue bars in Figure 4.

Taking into account the net benefit to the society calculated from the quantified risk assessment, it was recommended that a fixed fire suppression system should be installed in NTC. This recommendation was reviewed by the stakeholders in the Tunnel Design and Safety Consultation Group and accepted by the Tyne & Wear Integrated Transport Authority, as well as the UK Highways Agency.

The decision on whether or not to recommend a fire suppression system in the New Tyne Crossing was based purely on a cost benefit analysis. Intangible benefits, including the protection of the reputations and public confidence in the TWITA and the Concessionaire, have therefore not been included in the decision-making process.

The financial analysis was based on *societal* costs and benefits. For this reason, the loss of toll income to the Concessionaire was
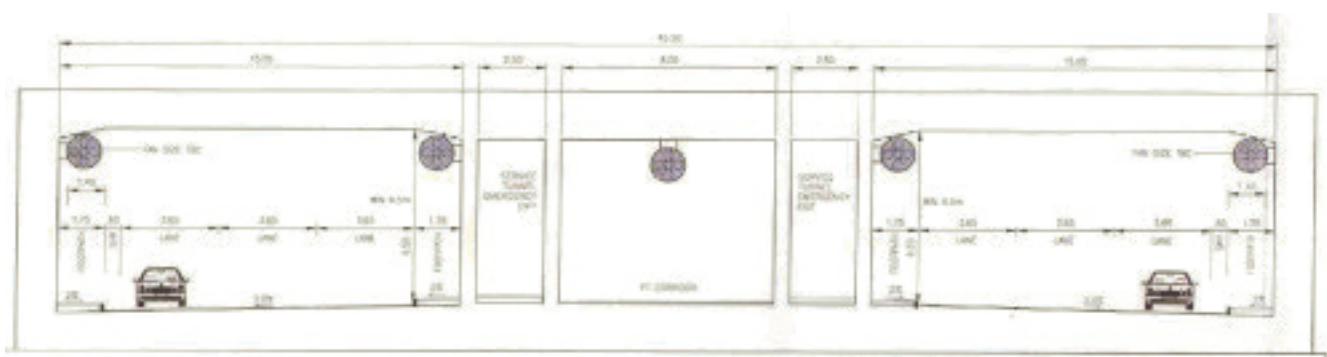

Figure 5: Original 5-Cell Design Option for Yas Island Southern Crossing Tunnel
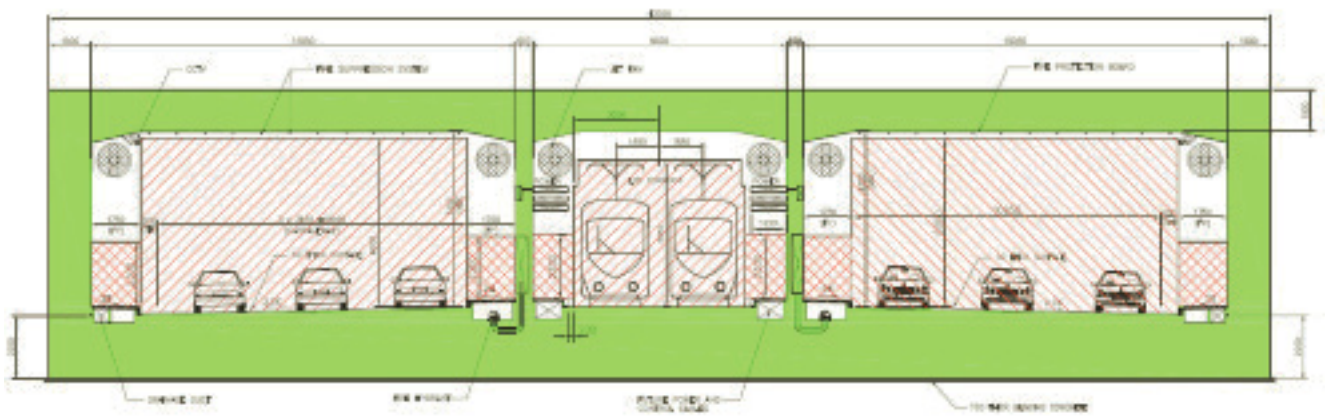
Figure 6: 3-Cell Design for Yas Island Southern Crossing Tunnel

not included in the analysis, since this is considered a private arrangement that does not directly impact on the rest of society. In contrast, the refurbishment costs following damage due to fire are included in the analysis, since society has to pay (perhaps through higher insurance premiums) for the reinstatement of the tunnel.

The decision to install a fire suppression system on the basis of a benefit-to-cost ratio (BCR) above unity may be controversial, since most of the benefits accrue from the reductions in traffic delays, rather than life safety benefits. The UK Highways Agency normally approves projects with a BCR above

unity that have life safety benefits, but the predicted life safety benefits here were relatively small. It is interesting to note that fire suppression is not being installed at the Hindhead Tunnel currently under construction in the UK, because the relevant BCR levels were reported to be below unity. Reasonable diversion routes are available in case of a major incident in that tunnel.

Another example of the application of risk assessment with respect to fire suppression systems is the Yas Island Southern Crossing, which includes a 698m long road tunnel linking Yas Island to the mainland of Abu Dhabi. The original 5-cell design concept included two

traffic cells, a Light Rail Transit (LRT) cell and two evacuation cells (Figure 5). Fire doors were to be provided between the traffic cells and evacuation cells at 100m intervals, in accordance with the UK's Design Manual for Roads and Bridges (BD78/99).

We undertook a quantitative risk assessment to study whether an alternative 3-cell design, which incorporated two highway cells and an LRT cell, would have an acceptable standard of fire safety (Figure 6). The 3-cell design implied evacuation distances of up to 294m to escape shafts on either side of the creek, but would benefit from a low pressure deluge fire suppression system.

BLANK

The quantitative risk assessment assumed that the design heat release rate from a heavy goods vehicle fire would be reduced from 150MW to 30MW due to the application of fire suppression. A fault tree analysis was conducted, which included consideration of cases with or without traffic congestion in the incident tunnel, and the timeline for the evacuation of motorists.

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. This is primarily due to the fact that the fire suppression system allows tenable conditions to be maintained for evacuation, under the majority of scenarios considered.

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).

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 greater 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 affected the 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.

The 3-cell design option was approved by Abu Dhabi Civil Defence, and the tunnel construction is currently nearing completion. In addition to a significant reduction in construction costs, the developer also benefited from a reduced risk to the construction programme.

As our understanding of the benefits, limitations and costs of tunnel fire suppression increases, improved methods and standards will be developed to reflect best practice in the world. This is likely to benefit designers, developers and authorities seeking to deliver a safe environment to motorists at an acceptable cost. ✔

Fathi Tarada

Fathi Tarada studied for a Bachelor's degree in mechanical engineering at the University of Sussex, UK, and carried on to undertake research work in gas turbine technology at the same university, for which he was awarded a Doctorate. He also has a Masters degree in business administration from the Open University. Fathi is a Chartered Engineer, a Fellow of the Institution of Mechanical Engineers, and a member of the Institution of Fire Engineers.

GOV. MONT