ABSTRACT
The paper advocates use of professional risk engineers and establishment of risk criteria to be met in vehicle tunnels. It outlines a methodology for establishing risk criteria and assessment of system effectiveness in risk reduction. It does not venture into the realm of quantification of risk, or of definition of a level of risk that the community will tolerate.

The Australian experience in using fire suppression systems in conjunction with smoke management systems is reviewed, and outcomes of a professional risk engineering study outlined. The additional 2-3% overall new tunnel cost for a suppression system is concluded to be worthwhile.

1. INTRODUCTION
There is a growing perception in the community that risk can be eliminated; that if risk remains, it is the fault or responsibility of someone other than the individual involved. Professionals and government bodies are being held accountable for issues that previously have had an implied acceptance by the community, as a tolerable risk. Decisions to travel are taken with every expectation of safe arrival; even with the knowledge of road injury and fatality statistics. Whilst there is a tacit acceptance by the community of risk in road travel, largely based on the traveller’s past experience, there is little understanding of the potential increase in risk involved in tunnel travel, especially in “long” tunnels. Engineers thus far have been making the decisions on behalf of the community in the provision of facilities they deem to be at a level of tolerable risk and at a reasonable cost for the benefit provided, based on judgement and experience. This position is now challenged. Additional safety facilities and reduction of risk are now being demanded by the community, but with no means of defining what is tolerable, acceptable or affordable. The paper seeks to make a contribution to the on-going debate by suggesting a methodology for the assessment of risk and explores the relative merits and effectiveness in risk reduction, of tunnel configuration, fire suppression and smoke management systems, and operator and emergency services response to an incident.

2. WHAT ARE THE THREATS? - RISK ISSUES
Risk is present in all vehicle tunnels and Table 1 schedules the main risks. This paper considers issues of risk associated with a fire incident only.

<table>
<thead>
<tr>
<th>Risk Issue</th>
<th>Threat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health and safety of the public, operators and emergency services</td>
<td>Air quality, vehicle accident, vehicle fire incident</td>
</tr>
<tr>
<td>Assets - tunnel facilities and user vehicles and goods</td>
<td>Vehicle accident, vehicle fire incident</td>
</tr>
</tbody>
</table>

Table 1: Vehicle Tunnel Risk Issues
Fire occurrence has been shown by PIARC data and tunnel operator records to be of low probability, and fires, when they occur, to be of low intensity and usually extinguished quickly by the motorist without assistance of trained fire fighters. Nevertheless the potential for a major disaster, involving loss of multiple human lives remains, as has been realised in several disasters in European tunnels in the past decade.

Prevention of fire is always a better option than measures to control or extinguish it. Control of a fire, once started, is a better option than dealing with the effects of a fully developed fire. Measures being adopted in major European tunnel new construction, and upgrade of existing facilities, are aimed at prevention as far as is possible, and/or dealing with the effects of a fully developed fire. Europeans are not yet embracing fire control, beyond that of Brigades intervention.

Smoke is known to be more of a threat to human life than the fire itself; both however can be lethal. There is now no argument among tunnel designers as to the need for a means of effective smoke management in the event of a tunnel fire; argument centres on how to achieve this.

Internationally, there are considerable differences of opinion and judgement in respect to provision of fire suppression systems, particularly sprinkler or deluge suppression systems. Designers either passionately believes such systems provide a substantial benefit in tunnel risk reduction or equally passionately, believe they present a substantial additional risk!

In Australia, there is no argument about this - we have universal agreement from authorities, emergency services, operators and designers that deluge systems provide a very worthwhile contribution to life safety, not otherwise available.

3. CURRENT PRACTICE - CONSENSUS AND DISAGREEMENT

There is an emerging consensus that in ‘long tunnels’ (whatever these may eventually be defined to be), where fully or semi transverse ventilation is a necessity for tunnel air quality control, the added benefit of containment of the smoke and hot gases by fresh air introduction either side of the fire site and exhaust at a rate of 200-250m3/s at (or in the region of) the fire site, is an effective solution.

In “short tunnels” there is no real consensus. Longitudinal ventilation is the preferred and lowest cost solution for tunnel air quality control and by developing a tunnel air velocity sufficient to prevent smoke “back-layering”, it is generally agreed that the ventilation can effectively protect vehicles upstream of the fire site.

Longitudinally ventilated “short” tunnels with free flowing traffic are less of a threat to tunnel occupants in a fire incident than are those with congested traffic. In free flowing traffic, vehicles downstream of the fire incident have every chance of exiting the tunnel before the fire develops and smoke envelopes the downstream tunnel section. In an urban environment where regional traffic congestion may well prevent vehicles downstream of a fire incident from exiting, longitudinal ventilation smoke management will propel smoke over vehicles trapped downstream, with a probability of injuries or fatalities.
Australian regulators have required a comprehensive range of smoke management and fire suppression measures since 1990, including use of multiple zone deluge systems in all tunnels. There has not yet been any attempt to define the type of smoke management system that should be used in urban tunnels where traffic congestion may be present concurrent with a fire incident. Nor has there been any attempt at quantification of probability and consequence of such an occurrence.

Australian tunnel deluge systems are required by authorities to:
1. Have a minimum discharge density of 10mm/m²/min, within nominated variance criteria
2. Achieve minimum discharge over the full width of the tunnel - including breakdown lane/bay and ramps
3. Have a zone length adequate to cover the longest vehicle permitted (usually 25 – 30m zone length)
4. Operate two zones and three hydrant streams at full design rate concurrently
5. Operate a third zone with a degraded discharge rate permissible over all operating zones
6. Have fully redundant water supply service capable of supplying the fire services for a defined period (up to 4 hours, depending on time for Fire Brigade to attend)

Currently European and USA designers have avoided use of suppression systems, as such installations are considered to present a higher level of risk in the tunnel than non-installation, and to not be cost effective. A number of reasons are cited to support this conclusion:
1. Possibility of spread of liquid fuel fire
2. Possibility of developing a dangerous situation from mixing water and chemicals spilt
3. Generation of scalding steam
4. Cooling of smoke causing smoke to drop to the human breathing level and general smoke logging of the tunnel
5. Inability to extinguish a fire located in a closed container, cabin or vehicle
6. Probability of non-operation of the fire water system from ice formation at sub-zero temperatures

In our view, each of these issues may be dealt with effectively by appropriate design response, such as by:
1 & 2 Appropriate grading of road surface, drainage and flame traps
3 & 4 Smoke management system capacity and development of containment air velocity at the ‘fire face’

**Figure 1:** Vehicle Tunnel Smoke Management Comparison

![Fully Transverse Localised smoke extraction](image1)

![Semi Transverse Exhaust Ducted Localised smoke extraction](image2)

![Longitudinal Smoke passes over entrapped vehicle downstream](image3)
Control of fire size to limit human exposure until the Brigades arrive for extinguishment action
Use of ‘dry-pipe’ distribution downstream of control valves and insulated, ‘trace heated’ pipe and storage

4. LEGAL AND TECHNICAL REQUIREMENTS

Arnold Dix\(^2\), lawyer and Professor of Engineering, has presented an excellent summary of the legal and technical requirements in respect to fire and life safety considerations for designers (Appendix).

Robinson, Francis & Anderson\(^3\) who practice in risk engineering and consulting, have similar observations in respect to risk (Appendix). In their view:

“The use of vulnerability assessments supported by cause-consequence models to assess risk in tunnels seems a peculiarly efficient form of ‘due diligence’ demonstrating that it is vital to give priorities to measures that will address matters before loss of control can occur. Regulators and corporate lawyers seem to find them attractive”.

There is strong agreement between these experts on the approach needed to address the legal and technical issues. There is a common emphasis on examination of every possible event and need for a considered response to each. Control - early control - is strongly advocated by the risk engineers; indeed they are unequivocal in their opinion that reliance on one measure (eg. ventilation) for smoke management, whilst allowing a fire to develop uncontrolled, would be a non-supportable position from a legal perspective.

The risk engineers also note “Risk control is primarily focussed at rare, high consequence events”. What does this mean in a vehicle tunnel? What is “high consequence”? In life safety terms, how many injuries or fatalities constitutes a community definition of “high consequence”. These issues need definition and determination so both risk engineers and tunnel designers can address them.

Relative risk can be established fairly readily, but this would not be sufficiently definitive for legal scrutiny. Table 2 schedules some examples.

Table 2: Vehicle Tunnel Relative Risk

<table>
<thead>
<tr>
<th>Relative risk</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi-directional traffic flow presents higher risk than uni-directional traffic flow</td>
<td>Vehicle collision potential higher with bi-directional flow</td>
</tr>
<tr>
<td>Long tunnel presents higher risk than short tunnel</td>
<td>Vehicle and occupant numbers likely to be trapped in long tunnel are greater</td>
</tr>
<tr>
<td>Urban tunnel presents higher risk than rural tunnel</td>
<td>Vehicle and occupant numbers likely to be trapped in urban tunnel are greater</td>
</tr>
<tr>
<td>Tunnel subject to traffic congestion presents higher risk than free flowing</td>
<td>Vehicle and occupant numbers likely to be trapped in congested tunnel are greater</td>
</tr>
<tr>
<td>Longitudinally ventilated tunnel presents higher risk than fully transverse or exhaust ducted semi-transverse tunnel</td>
<td>Vehicles and occupants may not be able to drive away from the smoke exhaust path (the tunnel vehicle envelope)</td>
</tr>
</tbody>
</table>

To move forward, quantified and agreed definitions of risk levels that match community expectations at a cost they are prepared to pay, are required.

Risk is influenced by decisions on the use or non-use of fire suppression or smoke management system, the design criteria to be adopted, the system type, and the interaction between systems. These then are not decisions designers alone should be called upon to make. Determination of risk level is properly in the realm of authorities and governments, who are the ultimate arbiters of community values, including definition of tolerable risk. A stronger lead is warranted in this area, than has yet been evident.
The role of the designer therefore, should be to define the options available and bring forward
the relative advantages, disadvantages and comparative costs, and the role of the stakeholders
and authorities should be to determine the tolerable risk criteria for design, and measures to be
incorporated.

5. RISK EVALUATION

Robinson, Francis & Anderson have provided a sensible methodology for evaluation of
vulnerability assessments, supported by cause-consequence models, to assess risk in tunnels.
Risk engineering specialists can provide the expertise for evaluation, comparison and even
quantification of risk which may then be related to known statistics with which the public are
familiar and tolerant, if not accepting. Tunnel risk may well be expressed in terms of
incidents, injuries or deaths/vehicle number/annum or incidents, injuries or deaths/vehicle
km/annum, or similar statistics.
Statistics exist for our major transport systems - roads and highways, railways, airlines -
against which projections for vehicle tunnels may be compared.
The tools exist for professional assessment of risk, but a benchmark of performance, needs to
be established by authorities and governments on behalf of the public, and the role of
professional risk engineers and methodology they adopt, agreed.

6. RISK CONTROL

Robinson, Francis & Anderson have noted a relationship between fire size and number of
deaths: “… There appears to be an empirical connection between the size of a fire and the
number of deaths. That is, small fires are less likely to kill people. The larger the fire the less
room for error there will be in any emergency response”.
Kumar comments on the danger of fire size: “It is the pre-flashover stage which is the most
relevant to life safety, for, if escape is not completed then, there is no chance after flashover”.
The obvious conclusions to be drawn from these sensible and readily accepted observations
are:

- Limit fire growth and size, so that flashover cannot occur.
- Limit fire size to the smallest practically possible.
- Limit the number of fire incidents.

Robinson, Francis & Anderson cite three primary risk control regions:

- Threat reduction
- Precautions
- Vulnerability reduction

In practical terms for the designers, this translates to:

**Threat Reduction:** Incident prevention measures.
Reduction of incident potential:

- Exclusion of large fire load vehicles or goods transported. In practical terms, this is not
  fully achievable. Rogue vehicles may enter a tunnel. Alternatively, large fire load
  vehicles may be scheduled to have ‘sole use’ of the tunnel at defined times.
- Improved tunnel geometry, alignment and information systems. PIARC data is
  available which indicates there is a correlation between vehicle incidents, tunnel
  geometry and advisory signs.
- Limiting vehicle numbers in the tunnel. Traffic management is inevitable, in congested
  conditions. (In the bi-directional Mont Blanc tunnel, vehicles must now maintain a
  minimum separation distance for increased driving safety).

**Precautions:** Incident management measures.
Limitation of incident magnitude:

- Identification by CCTV, traffic monitoring, fire detection, for early response.
- Initiation of suppression system. To provide a margin of safety, the suppression system capacity may be in excess of likely developed fire size.
- Effective smoke management system. To provide a margin of safety, the capacity of the smoke management system may be in excess of the likely suppression system controlled fire size.
- Early advice to emergency services for rapid response.
- Ready access to the incident by emergency services - vehicle cross-overs between tubes, breakdown lane in each tube.

**Vulnerability Reduction:** Evacuation measures.

Limitation of occupant exposure:
- Limiting vehicle numbers in the tunnel. Traffic management is inevitable, in congested conditions, to minimise the number of vehicles subjected to a potential threat and to maintain vehicle separation for driving safety.
- Smoke management systems to provide smoke-free escape paths.
- Simple, clearly understood communication with occupants.
- Public education in tunnel use.
- Design features facilitating prompt evacuation of all tunnel occupants.
- Prompt emergency team response.

The combined input of the whole of the design team, working in conjunction with professional risk engineers and operators is required for a full evaluation and quantification of risk issues.

7. **TIME - THE CRITICAL ELEMENT**

A lot has been written about the importance of actions to be taken within “the initial minutes” of a fire incident initiation. The importance of rapid detection, evaluation and response cannot be overemphasised. This involves everyone associated with the tunnel - operators, users, maintenance staff and emergency services personnel.

The response time capability is a function of the systems installed, operator training, tunnel length and traffic congestion in, and on the approaches to, the tunnel. A full response is unlikely to be in place in less than 20 minutes.

In the time the response is developing, the fire is growing in intensity, with the threat to tunnel occupants growing in scale, trending to exponential, with elapse of time. The possibility of a delayed response due to human error or system malfunction must be considered, together with a back-up response. Control and minimisation of the threat (the fire) at the earliest opportunity should be a prime consideration. Control of the (minimised) hot gases and smoke then becomes a less critical issue, and potential delays in emergency services access to the incident site become less critical.

If for no other reasons, these alone should be sufficient to justify incorporation of suppression systems, as is the practice in Australia where deluge systems are used.

Robinson, Francis & Anderson have, in their paper, focussed on the need for ‘control’ of the fire incident and have suggested a definition of the point at which ‘loss of control’ may occur:

"As cause-consequence models invariably demonstrate, control before the loss of control point is the only way to reliably prevent large scale multiple life loss scenarios when large energies and many people are involved” and “The loss of control point appears to be that fire which overwhelms the usual air handling system”.

The control point interpretation by Robinson, Francis & Anderson may not be acceptable to all. A very large capacity smoke management system may be provided to cater for the largest conceivable fire incident, including the ‘fanning’ effect of the ventilation system, which would meet the Robinson, Francis & Anderson ‘control point’ requirement. However, this involves a considerable installed cost, time for the system to develop a full response, and an acceptance of substantial collateral damage and consequent tunnel closure for repair as a consequence of an uncontrolled fire size.
8. SUPPRESSION SYSTEM BENEFITS

The needs, both technical and legal, to maintain the fire incident within the bounds of ‘control’ are obvious. Limiting the fire growth and intensity through early intervention is critical to the process of maintaining control, an issue Robinson, Francis & Anderson emphasise.

Suppression systems may not extinguish a fire, but they certainly do limit the developed intensity and in doing so provide an added margin of safety and outcome certainty by:

- Providing more certainty of maximum fire size, even with the wide variation in possible combustible materials, to which the smoke management system may be designed
- Limitation of gas temperature
- Limitation of radiation effects
- Reduced potential for structure and fit-out damage
- Reduced potential for smoke extraction system to be overwhelmed; rather it would be operating well within capacity
- Reduced threat to motorists and emergency personnel
- Closer proximity access to fire site by Brigades
- Enhanced prospect of maintenance of fire control in the event of one system’s failure
- Enhanced prospect of maintenance of control in the event of a delayed response initiation

It is a given that there will be a time delay between fire inception, detection of it, initiation of a response to it, and development of full effectiveness of the response. The earlier systems are operated after fire inception, particularly the suppression system, the more certain will be the ability to maintain control and to overcome the fire. Typically, activation of the suppression system within 5 minutes of fire initiation will limit the fire intensity to <16MW, based on a worst-case ultrafast $t^2$ fire growth.

Whilst the benefits of automatic initiation of a deluge system are advocated by Robinson, Francis & Anderson, the consequences of an accidental discharge or discharge at the incident site before vehicles are stopped, are not considered. A number of options are available for deluge system initiation which would minimise the possibility of human error or detection malfunction, including hybrid manual/automatic intervention.

In our opinion, detailed risk and technical evaluation of the full range of options for this important fire control system is warranted, for optimisation of approach.

Australian tunnel operators have acknowledged the benefit of use of their suppression systems on the several occasions when a fire incident has occurred. In each occurrence the fire size was quickly contained and size limited, and the tunnel operations (generating revenue) restored within about 2 hours, with little to no damage to tunnel facilities.

Based on the Australian experience, the cost of a suppression system will almost certainly be substantially less than a large capacity smoke management system; in most fire incidents it will prevent collateral damage and facilitate return to operation within 2 hours.

9. SMOKE MANAGEMENT ISSUES

Smoke in a fire incident is acknowledged to be a bigger threat to human life than the fire itself.

There is no universal acceptance on when or when not to select a particular type of ventilation system to address smoke management.

The following table summarises in simple form the complex and sometimes opposed considerations to be taken to account in selection of an appropriate ventilation system:
Table 3: Comparison of Vehicle Tunnel Ventilation System Characteristics

<table>
<thead>
<tr>
<th>Issue</th>
<th>Ventilation System Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fully Transverse</td>
</tr>
<tr>
<td><strong>Environmental performance</strong></td>
<td>Constant quality throughout tunnel length</td>
</tr>
<tr>
<td></td>
<td>Ducted exhaust: Increase in contaminants from supply to exhaust point</td>
</tr>
<tr>
<td><strong>CO Exposure</strong></td>
<td>Higher within same time frame than with longitudinal</td>
</tr>
<tr>
<td></td>
<td>Ducted exhaust: Same effect as longitudinal</td>
</tr>
<tr>
<td><strong>Smoke Management Performance</strong></td>
<td>Can exhaust directly from fire site in any length tunnel</td>
</tr>
<tr>
<td></td>
<td>Effective in unidirectional and bi-directional traffic flows.</td>
</tr>
<tr>
<td><strong>Relative Cost - ventilation and structures</strong></td>
<td>Highest cost system</td>
</tr>
</tbody>
</table>

**Figure 2:** Vehicle Tunnel CO Exposure

10. **A PRACTICAL USE OF RISK PROFESSIONALS**

Risk professionals were used to assess the relative merits of several alternative smoke management systems, with and without use of a deluge system, on a recent design proposal for an ~4km long twin tube, unidirectional, dual carriageway, urban tunnel. The design tolerable level of risk for the exercise was defined as not greater than that derived from incident statistics for comparable urban roads and highways. Risk analysis was
undertaken using the principles and processes espoused by Robinson, Francis and Anderson, which are referred to elsewhere in this paper. Longitudinal ventilation met the design criteria for air quality and was the lowest-cost in terms both of ventilation and excavation cost. However, the risk to motorists potentially trapped downstream of a fire incident in congested traffic was assessed to be much higher than the tolerable risk criteria. Provision of a separate smoke exhaust system (or a semi transverse ducted exhaust system), with exhaust capability focussed over a fire site at any point in the tunnel (multiple motorised dampers) was found to meet the tolerable risk criteria, but the additional excavation cost to house the exhaust system was considered prohibitive. A deluge system meeting authority requirements (costing <30% of a smoke exhaust system), acting alone with no smoke management system, failed to meet the tolerable risk criteria. The combination of limitation of the fire size by a deluge suppression system and a smoke management system of longitudinal ventilation, used in conjunction with enhanced emergency services access to an incident site, strict emergency handling procedures, and operator training, were then examined. The low probability of suppression system failure coincidentally with a congested tunnel occurrence, and the use of a smoke management system that was simply a ‘fire rated’ upgrade of the air quality ventilation system were shown to result in an acceptable outcome in terms of risk. The results of this study suggest that, from a meeting of tolerable risk criteria perspective, the limitation of use of longitudinal ventilation for smoke management to be in the range of 3-4 km, and require a robust suppression system. The professional risk analysis and the outcomes proved to be very helpful, both in the design process and in the development of optimised operational procedures.

11. RISK DESIGN CRITERIA

The ultimate criterion defining tolerable risk and the methodology for evaluation of risk needs to be established on behalf of the public by their representatives - the authorities and governments. Once established, recognised risk evaluation and quantification techniques may be adopted, as Robinson, Francis & Anderson³ have noted. Identification of potential threats will require input from the whole design team and stakeholders. Probabilities may be assigned to each threat, in conjunction with the risk engineers. Incident event and response times will require input by designers, operators and emergency services, with comment and review by the risk engineers. Definition of the point at which the fire incident is ‘out of control’ needs to be established and agreed and a factor of safety determined, to ensure loss of control does not occur. Limits to the many response time variables must be set and system design and operational response safety factors established to ensure the time limits are met. Review and revision will almost certainly be necessary to achieve acceptable outcomes for risk profile, system performance and cost benefit evaluation. Current Australian practice is empirically and prescriptively based, requiring design of fire suppression and smoke management systems for a single incident in one tube of the tunnel complex, usually of 50MW maximum fire intensity. This involves large capacity fire suppression and smoke management systems that, if activated at an early enough stage of the fire growth, may be shown by a professional risk evaluation to meet the tolerable risk criteria. Design for a 50MW fire may then not be justified, as such would then not develop. An overcapacity smoke management system in particular may involve considerable unwarranted excavation.
Alternatively, a professional risk evaluation may substantiate the added cost of the conservative approach, by quantifying the better risk outcome and potentially lower community cost from reduced injury or death incidents.

Risk studies inclusive of ‘worst case’ time scenarios for the various response activities to an incident may well substantiate adoption of lesser capacity fire suppression and smoke management systems than is current practice. Similarly, risk studies may well indicate longitudinally ventilated smoke management systems are not acceptable to the tunnel risk profile, particularly in ‘long tunnels’.

12. INCREMENTAL COST

Drencher fire suppression systems to address a 50MW intensity fire represent around 2-3% of the total construction cost of most tunnels, ‘short’ tunnels being at the high end of the scale. Smoke management systems of the longitudinal ventilation type utilise the system capacity required to address the environmental issues, as for all but ‘short’ tunnels, the air flow rate is determined by environmental, not fire criteria. Thus the cost for smoke management in such tunnels is related to upgrading the ventilation system performance criteria for operation at hot gas temperatures - a cost of less than 1% of the total construction cost of most tunnels.

If localised smoke exhaust is required, and a longitudinal ventilation system is adopted for normal operation, then a supplementary exhaust system is required. This involves an additional air passage/duct area of around 20-25%, consequent additional excavation beyond that required for the vehicle envelope, plus fire rated air passage/duct construction.

The added construction cost for a localised smoke management facility will be a function of the tunnel construction method, itself a function of the geotechnical characteristics of the excavated site. In sandstone/hard rock tunnels, the added cost will be proportional to the extra area over that required for the vehicle envelope - about 20-25%. In soft ground, using circular section tunnels, the added cost will be less than proportional to the air passage/duct extra area, as there will be ‘spare’ space available above, below, and to the sides of the vehicle envelope section. The added cost may be in the order of 10-15% overall construction cost.

Smoke management systems that do not propel smoke longitudinally, but have a capability of extraction from the fire incident area, may be incorporated in transverse or semi-transverse (ducted exhaust) systems. Additional excavation and cost would be of the same order of magnitude as for a localised smoke exhaust.

13. CONCLUSION

Community attitudes toward risk acceptance and expectations for safety have changed substantially since vehicle tunnels were first introduced. Internationally, many current vehicle tunnels fail to meet even empirically rated safety expectations of the community. The European Union has recognised this and has instituted a number of research programs to provide data for use in fire and life safety analysis and services design.

Professional procedures are available to assess and quantify fire and life safety risk in vehicle tunnels, to guide and recommend to authorities and governments and to work within the design teams to facilitate an understanding of potential outcomes in fire and life safety using the range of options being considered.

The community needs to accept that there will be added costs - both initial and ongoing - to achieve a higher level of safety in vehicle tunnels.

Use of vulnerability assessments supported by cause-consequence models to assess risk in tunnels provides a valuable means of evaluating threats, quantifying of risk and development of worthwhile cost-benefit comparisons from the range of design options available.

Use of professional risk engineers to assess smoke management and fire suppression system options has demonstrated the risk outcome benefits and cost minimisation benefits of combined smoke management and fire suppression systems.
REFERENCES

1. PIARC Road Safety in Tunnels, 1995
3. ROBINSON, FRANCIS and ANDERSON “Lessons from cause-consequence modelling for tunnel emergency planning”, Fifth International Conference Safety in Road and Rail Tunnels, 2003, Marseilles, France. Tunnel Management International

APPENDIX

Arnold Dix, lawyer and scientist, has presented an excellent summary of the legal and technical requirements in respect to fire and life safety considerations for designers:

Design Objectives

Technical: The design objectives may be a broad statement of what the final design is required to achieve
Legal: ...the objectives must be achievable and demonstrated to have been achieved.

Acceptance Criteria

Technical: The acceptance criteria are the benchmarks against which the design will be tested.
Legal: The acceptance criteria, which are set, provide pivotal and identifiable criteria, which can be examined prospectively to determine whether or not a particular design met the objectives.

Hazard Identification

Technical: Undertaking hazard identification for fire safety design of projects is a process that needs to involve all relevant stakeholders. The fire safety design provisions and procedures are required to integrate with operations.
Legal: In the future a hazard, which was not considered credible, may occur - and the fact that it occurred may be used as evidence that the hazard identification process was flawed. Alternatively despite identifying a potential hazard, its consequences might not have been fully appreciated. As a result the hazard may meet acceptance criteria and still fall outside the acceptance limitations. In both instances the allegation against the professional fire life safety engineer is that the failure to predict the event demonstrates the failure of the engineer to meet their professional standards. The test for professional liability, in almost all countries of the world, is not retrospective. That is, the test is related to what can reasonably be expected of the fire life safety engineer at the time they considered the issues - not after an event.

A. Dix “Building and infrastructure safety. Balancing legal and technical requirements”
Technical Paper, March 2002
Robinson, Francis & Anderson, who practice in risk engineering and consulting, have the following observations in respect to risk:

- Senior decision makers and the courts require a demonstration that all practicable reasonable precautions are in place.
- If something untoward occurs the courts immediately look to establish (with the advantage of 20:20 hindsight) what precaution/s that should have been implemented, weren’t.
- Risk is not strictly relevant since, after the event, likelihood is not relevant.
- Risk control is primarily focussed at rare, high consequence events.
- The lawyers/courts always focus on the prevention side first. Trying to restore control after the event is always difficult.
- As cause-consequence models invariably demonstrate, control before the loss of control point is the only way to reliably prevent large scale multiple life loss scenarios when large energies and many people are involved.
- The loss of control point appears to be that fire which overwhelms the usual air handling system.
- Emergency ventilation to prevent a situation becoming a confined space is an attempt to restore control and acts after the event.
- It is the change of the tunnel environment by the fire that creates the loss of control.
- There is a certain size fire that will disrupt the air flow, place remote persons at risk and thus bring about the need to impose emergency measures including an emergency ventilation system and the like. This appears to be the loss of control point.

Robinson, Francis & Anderson cite three primary risk control regions.

**Threat reduction** - ...reduce the source of fire, for example, combustible trucks with large combustible loads.

**Precautions** - ...such as deluge systems that can control fire before the normal air handling system is overloaded (small fires are safe fires)

**Vulnerability Reduction** - .... by ensuring no one is present during a fire (minimal stalled cars) and the provision of emergency response, ventilation and evacuation systems.

They further comment:

... There appears to be an empirical connection between the size of a fire and the number of deaths. That is, small fires are less likely to kill people. The larger the fire the less room for error there will be in any emergency response. With automatic operation, early in the development of a fire, small fires should be the norm. That is, flashover (well after the loss of control point) should not occur.

Robinson, Francis & Anderson “Lessons from cause-consequence modelling for tunnel emergency planning” - Fifth International Conference Safety in Road and Rail Tunnels, 2003, Marseilles, France. Tunnel Management International

Kumar comments:

*It is the pre-flashover stage which is the most relevant to life safety, for, if escape is not completed then, there is no chance after flashover.*


Robinson, Francis & Anderson summarise:

This (Kumar) argument is particularly powerful if there is stalled traffic in long tunnels with longitudinal ventilation. If the fire has achieved flashover the smoke has to be blown one way or the other potentially exposing up to half the tunnel occupants.