INVITED PAPER

RISK BASED METHODS IN TUNNEL DESIGN AND OPERATION

Paul SCOTT

BSc, MIFirE, MinstMan, Ove Arup & Partners, Risk & Fire Engineering
13 Fitzroy Street, London, W 1 P 6 BQ, UK

Key Words : *tunnel design and operation, accidents, fire, safety provisions, risk assessment*

Public attention has been focussed on the safety of travel through road and rail tunnels recently, due to the recent tragic accidents which have claimed hundreds of lives. Many consider tunnel safety to be based in the provision of mitigation systems, but examination of the facts and issues surrounding tunnel travel show that the problems and solutions are related the basic civil engineering design.

The achievement of an appropriate level of safety for tunnel users requires a balance between the requirement to simplify the design and operation of the tunnel and the necessity to provide safety systems, such as cross passages and ventilation, which may have very significant effects on the civil design. These systems are expensive and are not always appropriate, depending upon the length of the tunnel, traffic types and hazards to users.

In order to rationalize tunnel safety design, risk based methods are increasingly used. This paper describes the issues surrounding a risk based design methodology and discusses some of the major factors which effect the civil and mechanical design of tunnels and tunnel systems. In particular, the choice of single or twin bore rail tunnels, means of escape, design fires and ventilation are highlighted, using examples from current projects.

1. INTRODUCTION

(1) Tunnel life risk

The growing demand for new railways in highly populated areas, coupled with environmental constrains, is increasingly pushing road and rail transport underground. In general, with an increase in the proportion of a traffic route committed to tunnels, hazard to tunnel users is greater due to an increase in the consequences of accidents, related to difficulties associated with :

- Tunnel Users
  - —awareness by tunnel users in the vicinity of an incident that they are in danger
  - —reluctance to leave vehicles to utilize escape routes
- Tunnel Operators
  - —assessing and controlling a remote incident
  - —configuring active safety systems correctly with a shortage of information
- Emergency Services
  - —gaining entry to the incident tunnel
  - —setting up effective emergency operations within the required timescale

In addition, the increasing length of tunnels lead to a consequent increase in the frequency of accidents, related to the increased time vehicles spend in the tunnel. The tunnel environment, therefore, may result in an increased probability that an accident can lead to multi-fatalities and severe damage to tunnel structures, i. e. an increase in societal risk directly related to traffic routes with significant tunnel transfers. Although individual fatality risk may stay within tolerable limits, the societal or business risk may well be judged to be unacceptable.

Balancing this risk increase, a tunnel is normally a better controlled environment than open roads or fixed guideways, separating opposing traffic, not subject to poor weather conditions and provided with higher levels of monitoring, communication and safety systems.

However, despite increasing awareness of tunnel

Table 1 Recent Tunnel Accidents

Incident	Consequences	Comment
Baku **(Metro train fire)**	**289 dead** (249 on train 40 in tunnel)	Driver proceeded into tunnel with fire on train stopped to investigate then ran off. Passengers were evacuating in the tunnel when ventilation system reversed and many passengers enveloped in smoke.
Eurotunnel **(LGV shuttle)**	**No deaths or serious injuries,** Some smoke inhalation Tunnel shut for 3 months, Capital costs and loss of revenue >£20M	Ventilation not configured correctly for 30 minutes. System required 28 separate key strokes from operator for correct configuration
Swiss Metro	Some passengers suffered smoke inhalation	High level walkways in smoke layer, passengers descended to track bed to evacuate
Mont Blanc **(HGV vehicle)**	**43 dead** Tunnel shut for one year Significant economic loss to surrounding area	System wrongly configured by operators 35 people died in cars, 6 in tunnel, 2 in refuge French fire brigade attempted to advance 6 kilometres through smoke. Estimate of 75 to 100 MW fire size
Tauern **(HGV vehicle accident)**	**12 dead** Tunnel shut for several months	Accident at in-tunnel temporary traffic light. People did not evacuate initially as fire did not appear serious and control took no action to evacuate tunnel. Eventually fire spread to asphalt roadway
Kaprun	**189 Dead**	Fire in heater due to defective fan ignited hydraulic fluid and caused train to stop in a tunnel with considerable gradient. People attempted to escape uphill, enveloped by very toxic smoke

risk, and the application of technology to control and mitigate accident consequences, several serious tunnel accidents have occurred in the last ten years (see **Table 1**). These have mainly occurred in Europe, where stringent prescriptive codes of practice are generally applied to major buildings and civil structures. Furthermore, the tunnels have all been operating legally within the health and safety legislation of the countries in which they occurred.

The most compelling lessons from recent incidents[6),7),8)] suggest that complacency regarding the hazards to tunnel users and the miss-operation of complicated safety systems has lead to controllable accidents leading to significant numbers of fatalities. It can be argued that a tunnel design which enables the development of a *'good, simple'* emergency response would be better than one requiring *'sophisticated, complex'* systems and procedures.

(2) Public perception

Recent tunnel accidents and political decisions regarding safety spending have pushed the subject of risk and safety into public consciousness, highlighting the political and social nature of risk tolerability and standards of safety.

There appears to be a lack of confidence generally in the operation of many major systems (long tunnels, airport facilities, railway infrastructure) i. e. the public perception is that they present more hazardous environments than more traditional structures. This appears to stem from highly publicized accidents which may have been avoidable.

The risk to the public presented by major industrial and transport structures is in fact extremely low, lower generally than the background levels of risk already present and acceptable to society. For example, fire accidents often dominate the development of safety designs for rail tunnels, but in reality, the risk to individuals could be considered insignificant compared to other accident types (see **Figure 1**).

The reconciliation of public perception with objective estimates of risk is now recognized as an issue of considerable importance to engineers and their clients.

The threshold between individual and societal

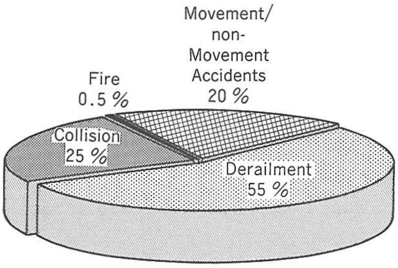

Fig. 1 Individual risk to regular high speed rail commuters

risk and their tolerability is, however, a public or political decision and can differ between systems and locations.

Following recent rail accidents, this issue is reflected in the many public debates in the UK surrounding the operation of the railway system and the benefit of advanced signalling systems, which have a tremendous (previously judged prohibitive) cost associated with them. While in the developing world, the approach to risk can vary tremendously, when the potential economic benefits to be gained by the users of infrastructure far outweigh considerations of minor risk to the public.

(3) Action by statutory authorities

The response from Government has been an increasing development of codes of practice which regulate tunnel designs. Many categorize tunnels into groups, prescribing safety systems for each category [2),3),4)].

The production of codes of practice is invaluable to the designer, providing guidance on good safety design practice and also representing what are considered to be acceptable safety levels for that society.

However, the design objective is ultimately concerned with successful operation of the system throughout the tunnel life-cycle (within the law, including safety law). In Japan, road tunnels are categorised as AA, A, B, C, D according to the total number of traffic kilometers forecast and the risk of accidents[5)]. For each category there is a prescribed requirement for safety equipment (see **Table 3**).

In Europe, a threshold of one kilometer is often used, regardless of traffic type[6)]. The use of this threshold appears to be completely arbitrary, as there is no evidence that risk increases significantly at this tunnel length; it appears that this threshold is chosen as it is a convenient unit of length used in that country. To apply this prescriptively may result in safety measures that are inappropriate, either significantly inadequate or grossly disproportionate for the tunnel considered.

(4) Disadvantages of prescriptive design methods

There can be serious dislocation between the objective of producing a static, prescriptive based design solution and providing a tunnel system which can be safely operated throughout it's life-cycle, as traffic and tunnel usage changes, caused by:

a) Lack of differentiation between tunnel traffic types
b) Lack of understanding (and comprehensive analysis) of safety hazards
c) Relating safety design thresholds to arbitrary units of length rather than any understanding of the relationship between safety risk and specific tunnel geometry
d) The use of prescriptive standards which do not assist tunnel operators to understand the changing nature of fire risk in their tunnels
e) A project which could produce a significant social benefit may not proceed due to the unacceptable cost of the prescribed safety measures.

To return to the lessons learned from recent major tunnel accidents, the identified problems mirror to same extent to recognized generic failures of the application of prescriptive codes to innovative structures. Increasingly, therefore, the application of formal risk assessment techniques is considered an important component of a major tunnel design and operation [4),7)].

2. RISK ASSESSMENT APPLIED TO TUNNEL DESIGN

(1) Safety standards and acceptance criteria

It is generally agreed that an *'absolute level of safety'* does not exist; safety in terms of the operation of systems is often defined as *'freedom from unacceptable risk'*. There has to be an acceptance of a certain degree of risk as a fundamental facet of system operation; this is true for traffic tunnels.

A general principle could be defined as 'no prac-

Table 2 Comparative accident statistics for five nations

	Killed per 100000 Population					Injury Accidents		Killed per 1 billion Veh·km		
	Total	Age								
		0-14	15-24	25-64	65 and more	per 100000 Population	per 1 mill. Veh·km	All roads	Outside Urban Areas	Motorways
Germany	9.5	2.4	23.0	8.5	10.6	482	0.62	12.2	-	4.5
Ireland	11.0	2.8	17.8	10.2	17.1	209	0.25[c]	13.1[c]	10.8[c]	7.4[d]
Japan	8.2	1.5	11.0	6.4	17.7	671	1.11	13.6	-	3.9
United Kingdom	6.0	1.9	11.3	5.6	8.2	407	0.53[b]	8.1[b]	8.4[b]	2.5[b]
USA	15.3	4.2	27.2	15.3	20.5	767	0.48	9.6	11.8	5.4

tice or activity involving risk should be adopted unless it produces a net benefit to society'. This principal allows the concept of net benefit to be judged in terms of the economic and social impact in different locations[1].

In terms of traffic tunnels, a practical safety aim can be defined as *'passage through the tunnel should not be more hazardous than on the remainder of the transport system'*. Tunnel operators cannot reduce the underlying risk of travelling, only mitigate the increased risk associated with tunnel use[9].

When assessing risks involved in the operation of a system the main tests involved are:

a) whether a given risk is so great or the outcome so unacceptable that it must be refused altogether, or
b) whether the risk is, or has been made, so small that no further precaution is necessary, or
c) if risks fall between the above, whether the risk has been reduced to the lowest level practicable (often referred to as—As Low As Reasonably Practicable: ALARP), bearing in mind the benefits flowing from its acceptance and taking into account the costs of any further reduction.

When used on different systems on international projects, therefore, design solutions may be developed according to the cost benefit perceived for particular safety designs philosophies.

Consider, for example, comparative accident statistics for five nations shown in **Table 2**. In order to define a region of "possibly unacceptable risk" data has been collected on road deaths, which are perceived as being a related risk to fire deaths in road tunnels. This was done to compare fire deaths with possible road deaths for the number of vehicle kilometers that will be traveled in the tunnel for a given year.

As shown in **Table 2**, on roads in Japan there were 1.36 fatal accidents per 100 million vehicle kilometers traveled in 1996. This data was taken from the International Road Traffic and Accident Database

Data from an independent source, the United States National Highway Transportation Safety Board, lists a fatality rate per 100 million vehicle miles of travel as 1.5 for 1999. This equals a fatality rate of 0.96 per 100 million kilometers, on the same order as the Japanese data.

It is clear that there are many factors that can inform where the risk criteria are placed for a project. To suggest outer bounds for the risk criteria, the figure below represents the bands within which the risk lines defining the ALARP region may be placed. If Japanese road death rate data is used as a benchmark, a risk line can be drawn to approximate "potentially undesirable risk".

In a recent major tunnel project, it was estimated that there would be slightly over twenty-six million vehicle kilometers traveled in a road tunnel per year, therefore, for a similar Japanese road tunnel, an automobile accident rate of 0.35 deaths per year would be expected.

The table also shows that accident rates are of the same magnitude in Japan as they are in the

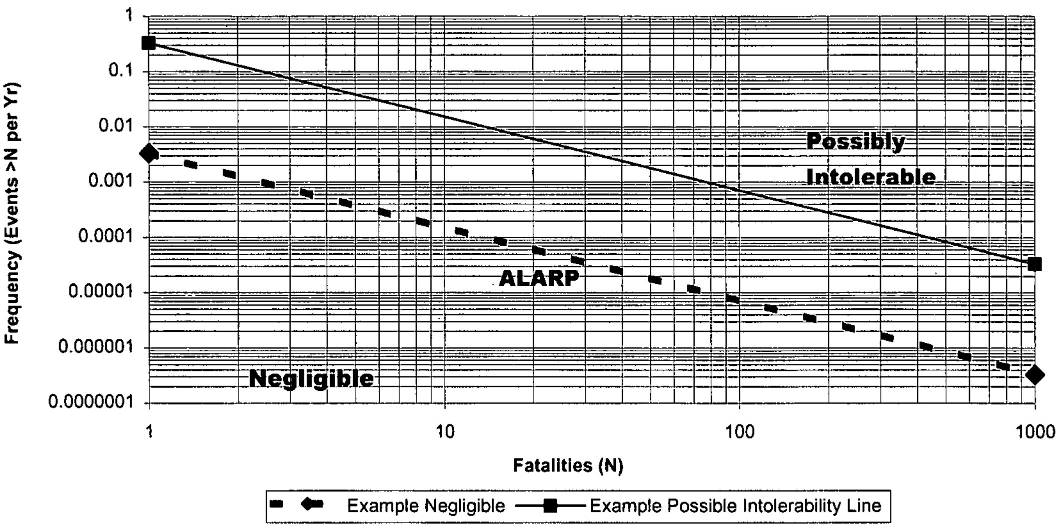

Fig. 2 Risk tolerability thresholds for a modern road system

Ireland, the UK and the US. If the road tunnel environment is considered to be equivalent to a motorway, this estimated casualty rate would reduce to 0.1 accident deaths per year.

This is a reasonable starting point determining the risk that the Japanese people are willing to assume, as they are already tolerating this risk on a yearly basis. However, there is generally a public aversion to multiple death accidents. Therefore constructing an isorisk line and assuming for example that the public would have the same tolerance for multiple deaths that they do for individual deaths would be inappropriate. The possibly intolerable line was therefore constructed steeper than an isorisk line.

Fixed lines defining negligible risk were developed based on judgements of the Canvey Island industrial complex in the UK report on Transport of Dangerous Goods [10], and were determined to be roughly two orders of magnitude below the possibly intolerable fixed line. These lines are shown in **Figure 2**.

It can be seen that by using the national experience of risk in road transport and comparing this with international statistics, reasonable thresholds for individual and societal risk may be developed, which can be utilized to inform decision making regarding the choice of effective and appropriate risk mitigation systems.

(2) **Risk assessment methods**

There are many tools available to assist the risk engineer to complete the risk analysis, ranging from spreadsheets to special risk assessment software, but to perform a valid and complete analysis and assessment, two phases of work are generally required:

- Qualitative safety assessment
  - —Hazard analysis
  - —Accident scenario identification
  - —Operability studies to assess the design concept
  - —Classification of risks
  - —Identification of preventative, control and mitigating measures
- Quantitative Risk Assessment
  - —Statistical analysis of the frequency and consequences of accident scenarios, from national and historic data
  - —Fault tree analysis, taking into account the safety measures proposed and their failure frequencies, to develop accident rates for vehicle kilometers run in tunnels
  - —Event tree analysis to consider the event frequencies and the overall individual and societal risk per yearly levels and inform decision making
  - —Production of risk estimates in comparison to tolerability criteria to demonstrate achievement of safety

In addition to the above, Operability Studies are advised, to link the Risk Assessment with the needs and capabilities of operators and tunnel users. Where the safety of tunnel users and operators is highly dependent upon active systems, systems assurance studies must also demonstrate the reliability, availability and maintainability of those systems.

(3) Disadvantage

However, there exists a problem with the application of these techniques; in some circumstances, the statistical data is available and is clearly relevant to the proposed design, but many major tunnels use new technology and systems may have little or no history of use and hence failure[1]. Therefore, significant parts (often the most significant) of the quantitative analysis of risk in new structures depends to a great extent on:

- The use of generic data adjusted to increase it's relevance,
- Professional judgement,

This can cause severe doubts and lack of confidence in the predictions of the risk assessment. In addition, many national authorities reject or are suspicious of the application of probabilistic analysis to design, particularly cost benefit analysis of the safety design, a technique which links the probability of an event, its cost in terms of fatalities (putting a value on a fatality avoided) and the choice of mitigation equipment.

(4) Benefits of risk informed design

For many major tunnels, the viability of the project depends upon new methods or ideas being used in the financing, design, construction or operation of the systems[8]. Existing prescriptive standards are often of limited applicability to such ventures. In particular when considering the achievement of design objectives, the adoption of prescriptive codes may be impossible or so restrictive that innovation is not practicable[9]. In these circumstances it is essential to use risk-based (or risk-informed) design techniques.

At the same time a greater understanding of the operational implications of civil design is required, particularly in the field of safety. As many projects are international, employing professionals and organizations from several different nations, some general consistency in the use of risk assessment to major tunnelling projects would provide significant benefits for the operator and user[2].

This is where the application of quantitative risk assessment techniques have been shown to be a valuable and flexible tool, allowing the social and political attitude to tunnel safety to be represented in the tunnel design.

(5) Successful adoption of risk based design methods

The success of the risk based design approach has been shown to require total commitment from the organizations involved, including Statutory Authorities. Corporately, the tunnel operator must be involved in producing a Safety Policy and Operational Safety Program. Statutory Authorities must be involved in the setting up of a regular consultation process, definition of methods to be used and determination of acceptance criteria. Finally, the risk based design techniques must be applied as early as possible, preferably at project inception.

Without this commitment, the process can become an ineffective exercise in producing paperwork, and provide little assistance to the ultimate tunnel user. It has been shown that the adoption this methodology provides effective and thorough mechanisms for the delivery of truly world class levels of safety and this approach to safety engineering and safety management is adopted by many major operators world-wide.

3. TUNNEL SAFETY DESIGN PROVISIONS

The range of tunnel safety measures for generally includes a combination of;

- Traffic control facilities, to facilitate the movement of traffic away from the scene of the incident, and to prevent traffic flow into the tunnel when an alarm is raised.
- Smoke control systems, to establish a clear route for evacuation and fire fighter access.
- Means of escape facilities, to provide a well-defined route for evacuation.
- Fire resistance requirements for business protection and to ensure the tunnel structure is not compromised during fire emergency operations.

Table 3 Emergency Equipment Provisions in Japanese Road Tunnels

Tunnel Category	Emergency Equipment	AA	A	B	C	D
Communication Alert System	Emergency Telephone	O	O	O	O	
	Push Button	O	O	O	O	
	Fire Detection	O	•	▲		
	Emergency Alert System	O	O	O	O	
	Traffic Signals	•	•	•		
Fire Fighting Equipment	Fire Extinguisher	O	O	O	•	
	Foam Hydrant	O	O	•		
Escape & Guidance Facilities	Emergency Exits	O	O			
	Escape Guide Panel	O	O			
	Smoke Management	•	•			
Other Equipment	Water Supplies	O	O	•		
	Sprinklers	O	▲			
	Radiating Cables (leaky feeders)	O	O	•		
	Broadcasting Facilities	O	•	▲		
	Loud Speaker System	▲				
	Video Monitoring System	O	O	•		
	UPS	O	O			
	EPS	O	O	•		
	Rescue Vehicle Entrance	•	•			

- Emergency service facilities, to enable the establishment of control and communications and fire extinguishing media supplies.

The above are generally accepted as basic components of a major traffic tunnel safety design[9]. Additional provisions, or an enhancement of the above (e. g. provision of fire detection, deluge systems) may be included to mitigate specific hazards. The use of risk assessment to assist in determining the level of provision and reliability of systems appears vital.

A typical Tunnel Categorization System, used in Japan, is shown in **Table 3**[5]. In the Japanese system, certain features may be either required, or recommended for consideration. The choice of which system to use and its specification can be assisted by using quantitative risk assessment and cost benefit analysis.

Some of the major issues which concern designers and operators regarding the choice and specification of these provisions are:

- The choice of Single or Twin Bore Rail Tunnels
- Means of Escape Provisions
- Fire Sizes
- Smoke Ventilation

These issues are discussed below, using examples from current projects.

4. SINGLE AND TWIN BORE TUNNELS

(1) Developing design standards

Design standards are now tending to require that twin bore tunnels are used exclusively in major road and rail projects[3]. This is in order to provide a means of escape via the non-incident tunnel, protected by ventilation. Other advantages can also be obtained by this design solution, such as maintainability and operational flexibility.

However, in certain circumstances, environmental or budget considerations might suggest that a single bore would be justified. Is it possible ever to justify a single bore twin track train tunnel for example?

(2) Major project example

Considering the fire risk, the larger diameter of a single bore tunnel provides a benefit to passengers in the event of a fire, as the smoke layer will be at a greater height[11], and conditions may be tenable for escape for longer, even without the provision of ventilation. Secondly, the development of a fire

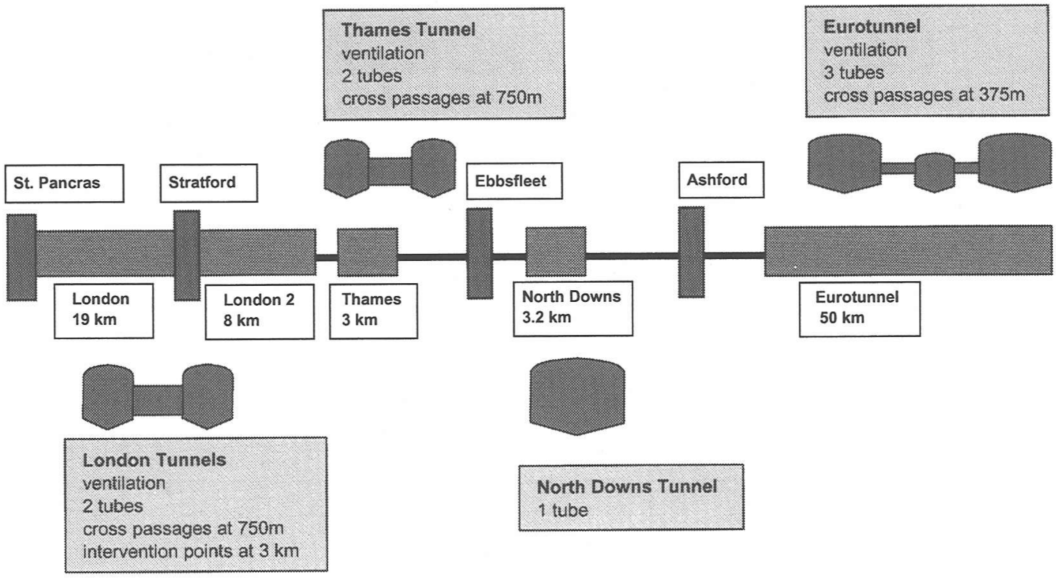

Fig. 3 Channel Tunnel Rail Link : Tunnel Designs

tends to be slower than with smaller diameter twin bore tunnels[12),13),14)].

In the Channel Tunnel Rail Link (CTRL) project, a 3-kilometer tunnel was proposed in the North Downs to protect ancient woodland. It was determined that a twin bore tunnel would cause unacceptable damage to the environment the tunnel was designed to protect. Furthermore, it was not acceptable to have either ventilation plant or an intervention point on the surface in the protected environment. The concept of single bore tunnel was proposed and Statutory Authorities consulted.

After detailed risk analysis, it was shown that a single bore tunnel with no ventilation system was the optimum safety solution in this case and the Statutory Authorities did not object to the design[10)].

The risk assessment was vital in this case, as the whole project could have been compromised if the single bore tunnel option was not acceptable.

Using the same risk based methodologies for the remaining long tunnels on the CTRL resulted in twin bore design, with cross passages and ventilation systems (see **Figure 3**).

This example shows how a risk based approach provides great assistance in identifying significant design options and enabling comparison of unrelated risk issues (passenger safety and environmental impact) within a consistent and logical framework, which can be used as the basis for decision making.

5. MEANS OF ESCAPE

(1) Recognition

Recent tunnel incidents have highlighted a very serious problem when attempting to design effective means of escape. Whatever facilities are provided, they are often not used by the public in a fire emergency. Deaths tend to take place in vehicles, either due to delayed response to the emergency or through difficulties leaving the vehicle[15),16),17)].

It is recognized that in Japan, considerable efforts have been made to inform the public about facilities available and how to recognize them[18)]. This initiative could be taken much further.

In Europe, for example, many drivers will pass through tunnels in different countries in the course of one journey, each with different signage for emergency exits, some more easily recognizable than others. Considering the expense of providing cross passages, direct exits or both, possibly linked to service tunnels, greater efforts to make their appearance consistent and recognizable in an emergency would appear to be obviously justified.

Many of the emergency exits in tunnels have signage based on typical building code requirements and are not easily seen even in the best visibility conditions. It could also be a logical step to improve signage and include recognition of these facilities in driving tests and public service broadcasting.

(2) Emergency exit spacing

The second issue of major concern is the provision and spacing of exits or cross passages. This requirement varies very significantly internationally. In Japan, for instance, a traffic tunnel in B category, carrying commercial traffic, is not required to have emergency exits, smoke management or an escape guide panel for tunnel lengths up to 3 kilometers, depending on the traffic volume[5]. This may well be justified in some circumstances, depending on the tidal nature of the traffic. However, in some modern rail systems, where fire and accident risk is very much lower, cross passages and sophisticated ventilation systems are provided[4].

The use of a risk-based approach would not necessarily change these decisions but would require a careful justification of the design solutions proposed, both in terms of safety and cost.

The fact that exits may not be immediately available has also to be considered. In the case of cross passages, until the traffic flow in the adjacent tunnel is stopped, it is extremely dangerous to allow uncontrolled access, especially in rail tunnels[9]. Thus the benefit of closely spaced exits must be carefully considered.

6. DESIGN FIRES

(1) Tunnel length and fire size

The 'design fire' and its relationship with tunnel length has a significant effect on predictions of tunnel conditions during emergencies; a credible, realistic design fire is a critical parameter when considering the type and capacity of fire safety provisions chosen for a tunnel design[9),10].

In particular, the design fire information enables:

- Determination of the acceptability, or otherwise, of the fire risk in the tunnel
- Determination of any requirements to limit or control hazardous traffic
- Appropriate choice of tunnel mitigation systems
- Specification of system design and capacity
- Development of operational procedures and emergency plans

It is essential, therefore, that design fires be based upon a comprehensive fire hazard analysis, taking into account fire parameters (heat release rate, smoke production versus time etc.) and probability of occurrence[10].

The relationship between design fire size and tunnel length is based upon:

- the increased fire frequency due to the tunnel traffic
- the potential for fires to develop without effective control
- the necessity to increase air flow in the tunnel to establish an escape route and the consequences of this action

(2) Fire development phases

The various phases of fire development and development times must be taken into account, in comparison with evacuation scenarios and times for escape to places of safety. When designing for means of escape in building design, the different phases of a fire, particularly growth time and associated smoke production, are taken into account. For tunnel means of escape design generally, the growth phase is ignored and the emphasis is placed on the maximum fire size.

The use of 'peak fire output', however, can result in design anomalies making the development of a realistic, simple and effective fire safety strategy almost impossible.

For instance, on the advice of a national institution, a rail tunnel risk analysis commenced on the basis that a fully involved multi-carriage train fire 'could not be ruled out' The analysis therefore showed that if it is assumed that an instantaneous 40 MW fire will be present in a rail tunnel the moment evacuation commences, it is impossible to provide a logical emergency operating procedure for tunnel controllers and fire services.

(3) Metro system case study

A recent case study[10] illustrated the potential importance of the growth phase of a fire in relation to rail tunnel length (see **Figure 4**).

One of the fire scenarios considered, on the advice of the Fire Service, was an internal baggage fire in a metro carriage. The typical limit of first-aid fire

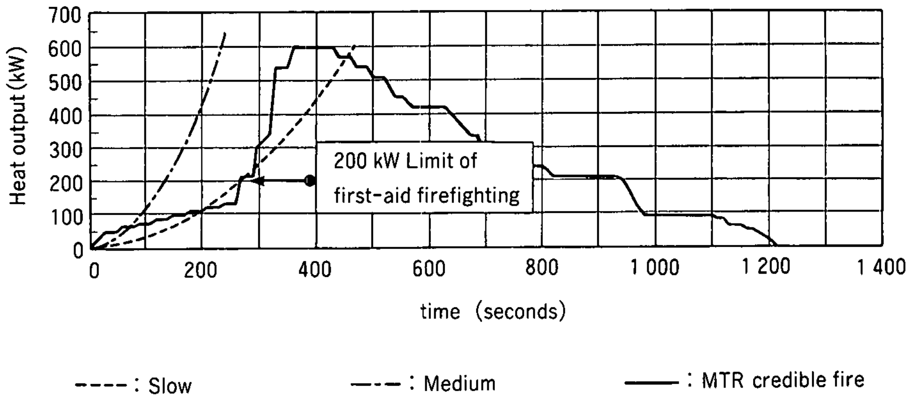

Fig. 4 Fire Development and Tunnel Journey Times

fighting (for the public) is considered very pessimistically to be 200 kW. Tests and modeling determined that the baggage fire would reach 200 kW after about 5 minutes. In this case, the average inter-station journey time was 2 minutes with the longest at 2 1/2 minutes.

Therefore, the fire alone would not prevent passengers evacuating at the next station, as it would not have reached a sufficient size during the inter-station journey time to threaten escape routes. The mitigation strategy then focussed on features which would prevent fire causing a train to stop in an uncontrolled manner and means to secure efficient evacuation from the train.

This is a simple example of how consideration of tunnel traffic hazard influenced a rail tunnel design and operational strategy. The design fire chosen can, however, vary significantly. For instance:

a) Considering a road tunnel with uncontrolled access for commercial traffic, credible fires may well be in the range of 40 MW (a very serious HGV fire) to 100+MW, with flammable liquid fires having the potential to develop extremely quickly (a petroleum tanker incident following an accident, for example).
b) In contrast, a modern electrified passenger rail system, credible fires may be in the range 2 to 8 MW, with the larger fires developing slowly and reaching their peak after the majority of passengers have evacuated the tunnel.

When the level of control, traffic characteristics, tunnel cross-section and likely tunnel population have been taken into account, therefore, estimates of tunnel risk may differ very significantly from accepted guidance or custom and practice.

The provision and spacing of cross passages and intervention points in tunnels can be a significant design challenge for new metro systems in an urban environment.

When the individual and societal risk from fire is estimated using the above method to determine credible fires, considering a range of tunnel lengths, interesting conclusions can be drawn regarding thew range of appropriate safety measures.

For a system that requires 'train-end' evacuation in the event of a fire, with escape in one direction, thresholds can be estimated regarding safety systems. **Figure 5** shows the risk to passengers from fire in the metro system, compared to the tunnel length between stations. It can be seen that for distances between stations of up to approximately 1.5 km, escape along the track bed to the nearest station provides a simple design solution and in this case, additional cross passages could not further reduce the risk.

For distance greater than this, methods for the emergency services to enter are important, as their intervention is of greater significance when evacuation times are extended, but the risk is still within tolerable limits.

For distances greater than approximately 3 km, cross passages become justified, to reduce the travel distance and allow the use of assisting trains to reduce evacuation times.

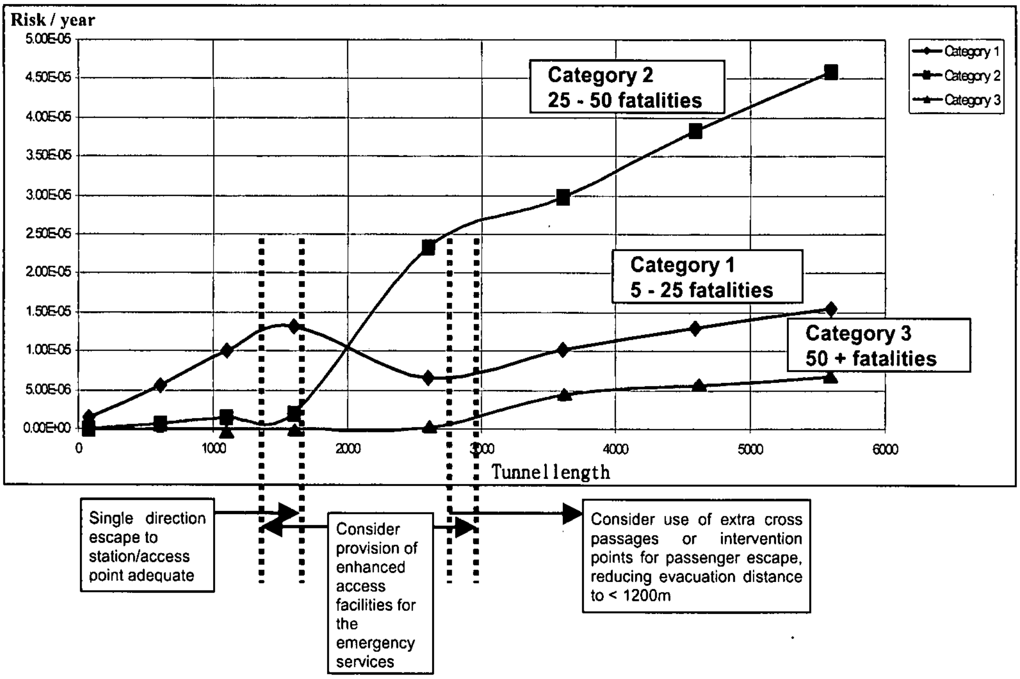

Fig. 5 Comparison of Metro System Tunnel length and Risk Mitigation Systems

7. SMOKE VENTILATION

It is generally accepted that in the majority of circumstances, smoke ventilation will provide a benefit in a fire emergency[2),3),4),7)]. However, the benefit may be to the tunnel user or the emergency services depending upon the operational procedures adopted. Ventilating a fire can be dangerous, as provision of oxygen may allow the fire to grow and spread, as in the Mont Blanc disaster and the Channel Tunnel fire[18)].

Some procedures state that the ventilation system will only be used upon the instruction of the fire brigade. This may take place a considerable time after ignition, depending upon the fire brigade arrival time.

In addition, in the case of rail tunnels, there is the problem of how to use the system, as typically with longitudinal ventilation, a significant number of passengers may have their escape conditions considerably worsened by operation of the ventilation fans[11)].

As this effect is noticed in nearly every disaster or near disaster, it might be reasonable to assume that the problem appears to lie with the overall fire safety strategy, including the choice of safety features, which is insufficiently robust to allow for operator errors in high-stress situations.

Using a risk based approach, including operability studies, it is recognized that systems, interfaces and operational procedures must be kept simple and logical.

Lessons from recent incidents[15),16),17)] suggest that a *'good, simple'* emergency plan is better than a *'sophisticated, complex'* procedure. For instance, a simple longitudinal ventilation system, linked with traffic control systems can often be shown by risk assessment to be the most cost-effective system for a road tunnel.

8. CONCLUSION

The increasing use of traffic tunnels and public perception of safety in their use requires action from both Statutory Authorities and designers. Prescriptive codes give useful guidance on suitable measures to enable the provision of tunnels which achieve required standards of safety.

However, a risk based design approach is required to enable a pro-active safety management which can achieve world class safety standards and potential improvements throughout a project life cycle. This approach requires commitment, cultural acceptance and timing for successful implementation.

Some of the major safety issues involved in tunnel design can be simplified using risk assessment, enabling projects to be completed where a prescriptive approach would seemingly rule them out. However, the approach needs to be used consistently through the design life-cycle to produce an integrated safety design.

REFERENCES

1) Health & Safety Executive: Quantified Risk Assessment-Its Input into Decision Making. HMSO. 1989. ISBN 0 11 885499 2.
2) World Road Association. Fire & Smoke in Road and Rail Tunnels. PIARC (Permanent International Association of Road Congress) Committee on Road Tunnels.
3) BD 78/99 Design Manual for Roads and Bridges; Design of Road Tunnels. HM Stationary Office 1999.
4) NFPA 130. Standard for Fixed Guideway Transit Systems. 083.74 NAT.
5) Design Guide for Emergency Facilities (Japan Read Association).
6) Federal Railway Office. EBA. Regulation. Fire and Disaster Protection Requirements for the Construction and Operation of Railway Tunnels. 01.01.1997.
7) HMRI Railway Safety Principles and Guidance. part 2 section Guidance on the Infrastructure. HSE HM Railway Inspectorate.
8) Project Delivery Models. Risk Assessment and Allocation for full Life Cycle Tunnel Management Covil. Grose and Plumbridge Ove Arup & Partners Tunnel Management 2000 m Sydney. Australia.
9) Scott. P. and Stokes. R.: The Design of a High Speed Rail Tunnel in an Urban Environment. Safety in Road and Rail Tunnels. 3rd International Conference. Nice. 9-11 March 1998.
10) Munro. J. and Scott. P.: Tunnel Design Fire Assessment. Tunnel Fires and Escape from Tunnels. 1 st International Conference. Lyon. May 1999.
11) To Blow or not to Blow. Charters Salisbury. Scott & Formaniak Ove Arup & Partners. Safety in Road and Rail Tunnels. 4th International Conference Madrid. April 2001.
12) How Much Do Tunnel Increase the Heat Release Rate of Fire Carvel. Beard+Jowitt. Herriot Watt University. Safety in Read and Rail Tunnels. 4th International Conference Madrid. April 2001.
13) A Study on Thermal Analysis for Tunnel Structures in the Event of Fire. Ota. Horiuchi. 4th International Conference Madrid. April 2001.
14) Major Fire Spread in a Tunnel; A non-Linear Model A. Beard. Herriot-Watt University. Safety in Road and Rail Tunnels. 4th International Conference Madrial. April 2001.
15) Task Force for Technical Investigation of the 24 March 1999 Fire in the Mont Blanc Tunnel; Preliminary Report of April 13. 1999.
16) Channel Tunnel Safety Authority. Enquiry into the Fire on Heavy Goods Vehicle Shuttle 7539 on 18 November 1996.
17) Hedenfalk. J. and Rohleh. P.: Lessons from the Baku Subway Fire. 3 rd International Conference on Safety in Road & Rail Tunnels. 1998. Nice World Road Association. Fire & Smoke in Road and Rail Tunnels. PIARC (Permanent International Association of Road Congress) Committee on Road Tunnels.
18) Analysis of Fire and Smoke Behaviour in the Channel Tunnel Fire and Mont Blanc Tunnel Fire. Bradbury. 4th International Conference Madrid. April 2001.
19) Trans Tokyo Bay Highway Corporation. Trans Tokyo Bay Highway Brochure; 1997.

(Received October 20, 2001)