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Assessment of the Safety of Tunnels

Study

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Preface

This paper is the final report for the STOA project 'Assessment of the Safety of Tunnels'.

The paper draws to a great extent on a literature search concerning the current status of risk assessment in relation to tunnels. It also draws on many conversations held with experts world-wide and to a small extent on the results of a questionnaire which was distributed to experts. Finally, it draws upon the discussions at a Workshop held at the European Parliament, Brussels, on 16th May 2007.

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Executive summary

This project results from concern about risk assessment following the large number of serious tunnel incidents that have occurred since 1995, many in Europe. It needs to be decided whether existing and new tunnels, and the systems associated with them, are acceptable with regard to risk. This, amongst other things, has led to risk assessment being incorporated into tunnel design. The questions arise: what constitutes 'acceptable risk assessment' and what might be an acceptable, common, system of risk assessment within the European Union?

Some key strategic issues to emerge are:

(1) Fatality, injury and harm result from the working of a system. Risk assessment, therefore, needs to be as 'systemic' as possible. How do we do this?

(2) The 'system' leading to fatality etc., is continually changing; how do we create a risk assessment structure which is capable of coping with this?

(3) Risk assessment implies the use of models and models have the potential to produce poor design and, possibly, disaster; because of uncertainty, flexibility of application or inappropriate interpretation. How do we create a risk assessment system which will ensure, as far as possible, the acceptable use of models as part of tunnel safety decision making?

(4) Using risk assessment methods means having a knowledge base to support it. As 'the system changes' that base needs to be continually sustained and that means independent research with publicly available results, giving theoretical tools, experimental results and statistical data. This needs to be on-going.

(5) What is a 'healthy mixture' of prescriptive requirements, qualitative risk assessment and quantitative risk assessment?

(6) Criteria for acceptability of risk need to be decided. This is essentially an ethical, and therefore social and political, question rather than technical.

Some key specific issues to emerge are:

(1) Most fatalities in road tunnels result from accidents that do not involve fire. A concerted effort needs to be made to address this. Fire related incidents are more likely to result in multiple fatalities and heavy goods vehicles (HGVs) present a major problem. This needs to be addressed.

(2) Historically, the risk in rail tunnels has been lower than for road tunnels. However, this should not induce a state of complacency. In 1998, the road tunnel risk may have been regarded as not a great cause for concern, judging from historical statistics at that time. The rail tunnel stock in Europe is old, the average age being about 70 years; this is a cause of concern. Further, possible new risks resulting from high speed rail lines need to be comprehensively addressed.

(3) For both road and rail tunnels: are the measures in place for non-malicious incidents adequate for malicious incidents? Also, what might be the effects of global warming and rising sea levels on tunnel safety?

Other strategic and specific issues are identified in Section 7. Recommendations are given in Section 8.

Contents

1 Introduction

This final report relates to a ten month research project which finished on 15th October 2007. The context of the project is concern about tunnel safety following the series of major tunnel fires, many of them in Europe, which have occurred since 1995. The focus of the study has been on the process of risk assessment rather than specific factors affecting risk in tunnels per se.

Further, the intention is to attempt to consider more generic issues affecting tunnel safety risk assessment rather than to examine specific techniques in detail.

1.1 Aim

The aim of the project has been to examine approaches to tunnel safety risk assessment and the issues which arise, with a view to making recommendations for moving towards a common system of risk assessment for the European Union. Both road and rail tunnels are given consideration. Categories not included are: (1) tunnels under construction, (2) malicious acts, (3) underground railway/metro systems. Even though these categories are nominally not included, mention has been made of them to some degree.

1.2 Approach

The approach taken has been wide-ranging and, to some degree, ‘blue skies’. It is considered to be desirable to look at other sectors and not to adopt a narrow perspective; to consider relevant experience in other areas, not just that directly found in tunnel operations. The emphasis is on conceptual matters rather than statistical or quantitative detail.

In order to conduct the project, the following has been undertaken:

a) A literature review: to ascertain the range of methodologies, techniques, and models which have been reported in the scientific literature, together with problematic areas, and to elicit relevant issues.

b) Consultations with experts: interaction with experts has taken place, long-distance and directly via meetings. As a vehicle to aid this, a questionnaire was employed.

c) Particular tunnel cases: consideration of a few individual cases has taken place in order to try to determine which general approach was adopted (or is being adopted) with regard to tunnel safety risk assessment. This is sometimes described as a determination of ‘best practice’. However, there is no universal agreement as to what constitutes ‘best practice’; the practice undertaken in any project, even a current one, may not be ‘best’. Having said that, there may be certain design features or procedures that are generally regarded as ‘best’ at any given time.

   The remainder of this report is based upon an assimilation of what has emerged from the project. For a general reference, containing a large number of references on particular topics, see [Beard, A. N.; Carvel, R.O., 2005].

2 Setting the scene

Information on accidents in tunnels does not appear to be collected on a European or world-wide basis and even on a national basis it is often difficult to find such information. However, some general trends seem to be:

For road tunnels [Bird, S. et al., 2005]

- Accident rates appear to be slightly lower in tunnels than for uncovered roads;
- The approach zones to a tunnel are more dangerous than the central section of a tunnel;
- Non-fire incidents are more numerous than those involving fire.

Most fatalities in road tunnels appear to arise from ordinary traffic accidents. Norwegian data [Musaeus, S. U. et al., 2004] indicate that, very approximately, two-thirds of deaths result from common traffic accidents and about one-third from fire related incidents and ‘dangerous goods’ incidents, see Table 1. As ‘dangerous goods’ incidents are likely to involve fire, this may be assumed to be about one-third from fire-related incidents.

Table 1: Life Loss in Road Tunnel Incidents in Oslo

Type of Incident	*Potential loss of life (PLL) per billion person km*	*Percentage (%)*
Common traffic accidents	0.74	67
Fire, Light vehicle	0.08	7
Fire, heavy vehicle	0.24	21
Fire in tunnel installations	0.01	1
‘Dangerous goods’ incidents	0.04	4
Total	1.1	100

Because most deaths result from common traffic accidents it is essential to address this as well as fire-related incidents which are more likely to result in multiple fatalities. In particular, measures to help to avoid collisions need to be very seriously examined; for example, barriers and measures to control vehicle speeds and inter-vehicular distances. Such measures would also help to avoid fires and control their spread. Creative thinking is called for - for example, the use of a large laser-projected ‘STOP’ sign onto a water curtain, which is being tested at a portal to Sydney Harbour Tunnel to stop effectively vehicles entering the tunnel during an incident (Preventing vehicles entering a tunnel during an incident is more difficult than it might seem.) This helps to reduce the chance of accidents and also of fire spreading to other vehicles. Measures adopted may be relatively simple, such as having a white road surface instead of black to improve visibility (as in a Swiss tunnel); further, this helps to save energy. Also, a regulation to establish an offence of non-observance of vehicular spacing might be considered, as suggested in the report which followed the study commissioned by the French Parliament after the Mont Blanc fire of 1999, [OPECST, 2000]. These are just examples, aimed at avoiding traffic accidents; a comprehensive consideration is necessary.

For rail tunnels it is more difficult to obtain information on accidents; it becomes necessary to track down individual incidents and accident reports in *an ad hoc* way. The most serious rail tunnel incident ever seems to have been in the Armi tunnel, Italy, in 1944 which resulted in approximately 450 deaths, mostly from carbon monoxide inhalation.

Fatality rates for entire railway networks for several countries (Denmark, Sweden, UK, France) indicate that the number of fatalities per billion person km is very approximately 0.25, see [Andersen, L.W., 1998], which makes it significantly less than for road networks or road tunnels. Data collected at a European level for the entire railway network indicate that accidents involving fires are a small percentage, 'Fires in rolling stock' constitute only 3% of all accidents on the railways [Eurostat, 2004]. The insurance company Munich Re has estimated that it is about twenty times more likely that fire will break out in a road tunnel than in a rail tunnel [OECD, 2006].

Although accident rates in both road and rail tunnels do not appear to be exceptionally great overall and fires are not especially common in tunnels (although in some systems, e.g. some metro systems, the rate of occurrence may possibly be higher than in most tunnels; the position is not very clear) it is the case that if a fire takes place in a tunnel then the consequences can be expected to be far more severe than a similar initial fire in the open air. This is because heat and smoke are trapped within the tunnel, creating positive feedback and helping to make the result worse and quite possibly catastrophic. All of the major tunnel incidents since 1995 have involved fire, as far as we have been able to ascertain.

A list of significant tunnel fires from 1842 to 2004 has been published [Carvel, R.; Marlair, G., 2005]. This details all the significant fires in tunnels on which the authors were able to glean information, from many different sources. Undoubtedly it is incomplete but it does provide a basis for some analysis to enable some broad brush conclusions to be drawn. The list has been brought up to date by the investigators in this project by including information on significant tunnel fires which occurred in 2005 and 2006; see Figures 1-5.

Figure 1: Road Tunnels: number of significant fires world-wide (1987-2006). Total = 49 (inc. 43 in Europe; not inc. during construction or malicious)

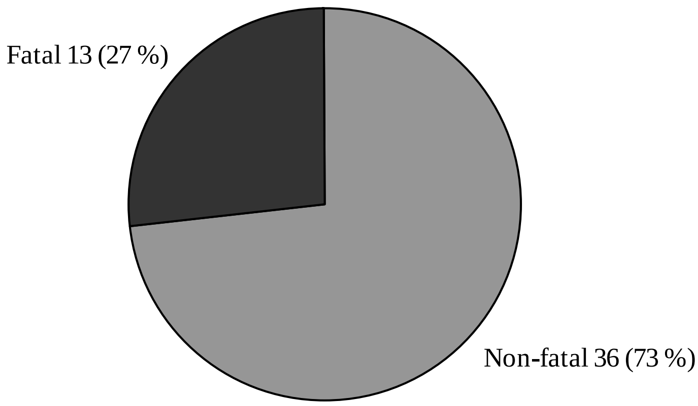


Figure 2: Road Tunnels: numbers of fatalities in fires world-wide (1987-2006), by vehicle involvement. Total = 96 (Not inc. during construction or malicious)

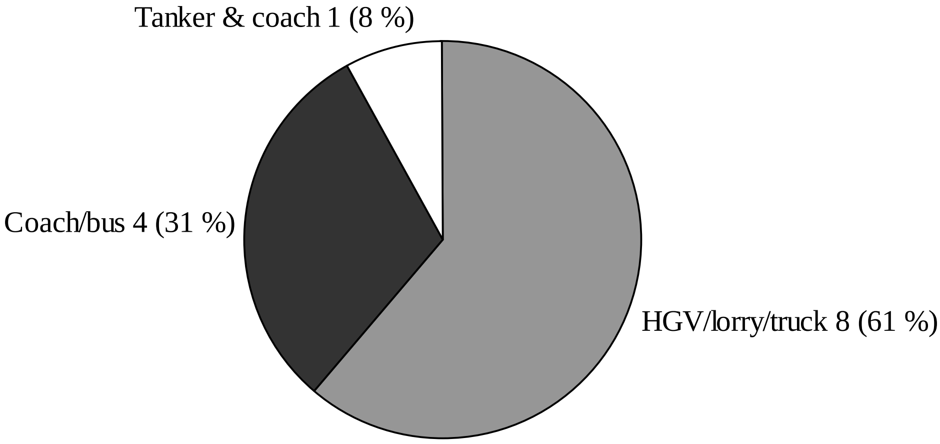


Figure 3: Road Tunnels: numbers of fatalities in fires world-wide (1987-2006), by vehicle involvement. Total = 96 (Not inc. during construction or malicious)

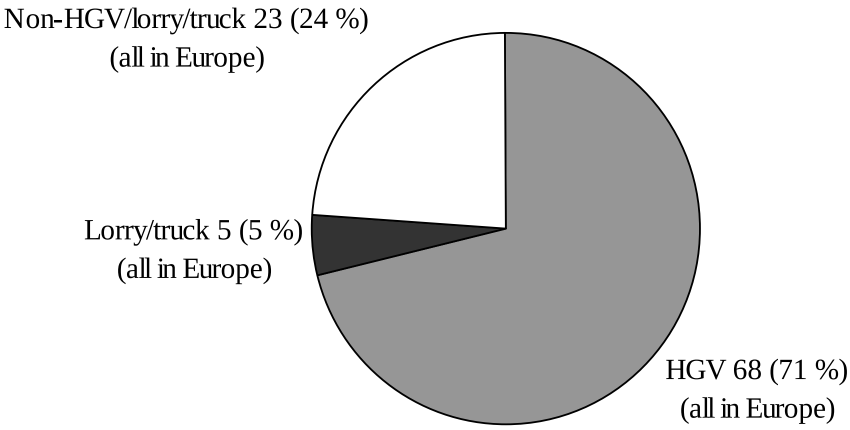


Figure 4: Rail Tunnels; number of significant fires world-wide (1987-2006). Total = 14 (Not inc. during construction, malicious or metro systems)

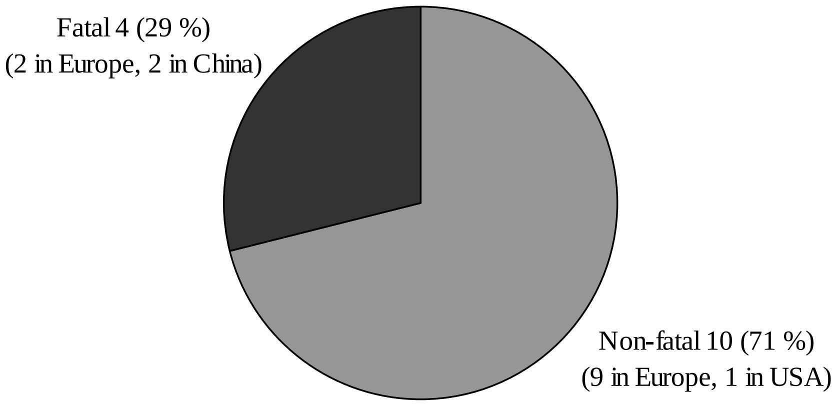
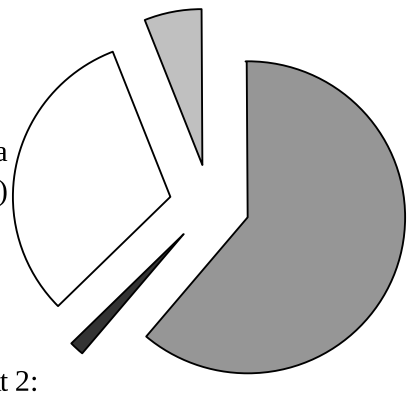


Figure 5: Rail Tunnels; number of fatalities world-wide (1987-2006). Total deaths = 254; number of incidents = 4 (Not inc. during construction, malicious or metro systems)



In the information available, a vehicle has sometimes been described only as a 'lorry' or 'truck' without specifying whether it was a heavy goods vehicle (HGV) or lighter vehicle. In Figure 2, these have been combined with those specified as 'HGV'. In Figure 3 vehicles specified as 'HGV' have been distinguished from those specified only as 'lorry' or 'truck'.

It can be seen that HGVs have been a major factor in most serious road tunnel fires during the last twenty years. For example, in the Mont Blanc Tunnel fire of 1999 several HGVs were involved and 39 lives lost; it took 53 hours to extinguish the fire [Carvel, R.; Marlair, G., 2005]. Also, in the Channel Tunnel (rail) fire of 1996, HGVs were centrally involved [CTSA, 1997]. It is only by sheer luck that there were no fatalities in this fire. If the fire had started in a HGV near the amenity coach end of the train instead of near the other end, it is almost certain that there would have been fatalities (The amenity coach carried the HGV drivers). A second fire occurred on a HGV in the Channel Tunnel in 2006 but fortunately it was extinguished relatively quickly [BBC, 2006]. In both these fires passengers and crew were evacuated via the service tunnel. In the figures above it may also be seen that coaches or buses have been involved in many fires in road tunnels.

It is evident that it is not only vehicles (usually tankers) carrying loads designated as 'dangerous goods', such as petroleum or liquefied petroleum gas (LPG), which should be a major cause of concern. This point is made in [OPECST, 2000]. HGVs carrying 'ordinary' loads such as furniture are also very dangerous factors in tunnel fire risk. To a lesser extent this may also be said of lighter goods vehicles and coaches/buses. To refer to loads such as tanker loads as 'dangerous goods' implies that other 'ordinary' loads are not dangerous; this is far from the truth. Many vehicles (including their loads) other than those classified as carrying 'dangerous goods' are also dangerous. In the USA, the vehicle datum to be used for tunnel design (i.e. the design fire size) has just been increased for a HGV fire from 30MW to '70-200MW', [NFPA, 2008]; the latter is much more realistic, see [Ingason, H. & Lonnermark, A., 2005], [Carvel, R., Beard, A.N. et al, 2005]. In Europe a similar change has not yet come about, as far as the authors are aware.

Some ‘ordinary’ loads are less dangerous than others. For example, in the Channel Tunnel fire of 1996, a lorry carrying pineapples seems to have helped to retard the progress of the fire along the line of carriers. It would be desirable to ‘space out’ less dangerous loads on lorries passing through a tunnel. The nature of the vehicle construction and the age of the vehicle, are also important factors. In [OPECST, 2000] it is pointed out that differences in the price of fuel in different countries is leading to larger fuel tanks in HGVs. If fuel prices were uniform there would be less or no incentive to have large fuel tanks; a haulier would presumably be more willing to carry extra goods rather than extra fuel (Such a measure would be expected to aid non-tunnel road safety as well.) Further, there is a strong need to control inter-vehicular distance for HGVs, including the need to prevent drivers parking too close behind another vehicle during a fire incident, which may lead to a rapid spread of fire from one vehicle to another, i.e. a ‘domino effect’ as seen in the Mont Blanc fire, [OPECST, 2000]. The point is also made in [OPECST, 2000] that Switzerland and Austria were pioneers of the concept of carrying vehicles on carriers through tunnels (‘Piggyback traffic’), a modern incarnation of which may be seen in the Channel Tunnel. Notwithstanding the Channel Tunnel fires, the ‘Piggy back’ concept does offer a much greater ability to control the traffic going through tunnels and it would be desirable to consider the feasibility of such a system in a new tunnel or upgrading of an existing tunnel.

During the first three months of 2007, three significant fires in tunnels have come to light:

(1) February 14th, Hong Kong, China: A voltage transformer mounted on the roof of a car of a train caught fire. It tripped the overhead line supply and the train was brought to a stop by the driver for emergency evacuation of passengers, [KCRC, 2007]. The report does not mention any casualties resulting.

(2) March 4th, Wisconsin, USA: a fire in a water intake tunnel (under construction) lasted over thirteen hours. There were no injuries.

(3) March 23rd, Burnley Tunnel, Melbourne, Australia: a sequence of events was initiated by a lorry having a burst tyre. Ultimately a crash involving three HGVs and four cars produced a fire during relatively heavy traffic. Three people in three separate vehicles were killed. The Burnley Tunnel is twin-tube with three lanes to each tube; it has a water deluge system and a dedicated smoke extraction system. Control room staff were alerted via closed circuit television (CCTV) and manually activated the deluge system within two minutes. This stopped the fire spreading beyond the immediate area; smoke was confined to one extraction point zone. The fire was extinguished by the fire brigade approximately one hour after the start of the incident. About 400 people were evacuated [ABC, 2007], [Johnson, P.; Barber, D, 2007].

    It is likely that the seemingly integrated functioning of the system (i.e. primarily: deluge/smoke extraction/control room reaction and fire brigade intervention) avoided a much larger catastrophe, although, tragically, three lives were lost. Questions that come to mind relate to how traffic accidents in tunnels might be avoided and control of lorries. Fire suppression systems are generally not installed in European tunnels.

In Europe the overwhelming majority of goods is transported by road, see [OECD, 2006]. Further, it appears that the current market share of rail freight (8%) is set to fall further still, and this share is much lower than e.g. the USA, [op. cit.]. This means that the problem of freight transport through road tunnels is likely to increase in the coming years. Efforts are needed to try to reverse this trend. This would have significant environmental benefits as well as safety benefits.

(For information, it may be said that the [OPECST, 2000] report referred to above resulted from a study carried out by the French Parliamentary Office for Evaluation of Scientific and Technological Choices, in the wake of the Mont Blanc disaster. The study covered French, and a few cross-border, road and rail tunnels of lengths greater than 1 km; 39 road tunnels and 116 rail tunnels. The report makes general recommendations and specific recommendations on the Mont Blanc and Channel Tunnels. Overall, the tenor of the report was not optimistic about the state of safety of tunnels in France. The point may be made that most, if not all, other countries are unlikely to be in a position to be complacent. Were similar studies to be conducted in other countries then similar conclusions may be drawn.)

3 Tunnel Design and Risk Assessment

3.1 Prescriptive requirements

The traditional approach to design of the built environment, with regard to safety risk, has been to learn directly from experience, with building regulations stretching back over many centuries and even millennia. During the 20th Century such regulations came to be called 'prescriptive regulations'. These are intended, in principle, to be universally, or at least generally, applied. In practice there has usually been the possibility, in regulatory frameworks, of not applying a particular prescriptive regulation in a given case, if the regulatory authority could be persuaded to accept it. Such deviations would, however, be the exception rather than the rule. Within a prescriptive approach, the risk level would not be explicitly realised at the design stage but would be implicit within the system designed. The risk associated within a given design would, perhaps, come to be realized after design, construction and operation, i.e. historically. An example of a prescriptive requirement is that contained in the EU Directive on road tunnel safety [EU Directive, 2004]: "In any case, where, for tunnels at the design stage, a 15-year forecast shows that the traffic volume will exceed 10000 vehicles per day per lane, a twin-tube tunnel with uni-directional traffic shall be in place at the time when this value will be exceeded.". Although this is essentially a prescriptive requirement, there will be uncertainty in the estimation of the future traffic volume; it will depend upon how it is estimated and that allows for different assumptions and models. Even with this (ostensibly) straightforward regulation there is flexibility and uncertainty in its application. This serves to make the point that, in reality, relatively few 'prescriptive regulations' are actually purely prescriptive.

Prescriptive requirements, generally built up over many years, represent a rich seam of knowledge and experience and, until relatively recently, have formed the bed-rock of design of the built environment. There are good reasons why this approach needs to be modified but it would be wise for any future regulatory system to retain a large element of prescriptive requirements.

3.2 Risk Assessment as part of Design and Operation

A problem with a regulatory system based purely upon prescriptive requirements is that the degree of flexibility it allows is limited [Beard, A.N., 2005]; some of what follows derives from this reference (Even so it should be noted that at least one major country, with a large number of tunnels, i.e. Japan, has not generally embraced risk assessment (i.e. not quantitative risk assessment at least); see Section 7, point [4] of this report.).

Flexibility allows certain considerations to be taken account of, that is:

a) No two tunnel systems are the same. There are generally differences of length, cross-section, construction, terrain, gradient, ventilation conditions, types of traffic and users, operational system, emergency service arrangements etc

b) The system changes. For example, vehicle volume and type may change over the years and this has certainly happened in Europe [OECD, 2006]. Prescriptive requirements appropriate for one time may not be appropriate for a later time. If risk is assessed on a continual basis then such changes should be picked up explicitly. They should then be acted upon, if necessary. Also, in principle, all aspects of a system should be considered.

c) New materials and techniques may not be adequately accounted for by a purely prescriptive system. That is, new materials may not be allowed in a given prescriptive system.

Also, some new materials and techniques may be allowed but may have hazards associated with them as well as advantages. These may not be explicitly realized in a purely prescriptive system.

d) Different options may be devised which are, in principle, estimated to have a similar risk associated with them. Such options are often called ‘equivalent’ with regard to the risk.

e) There may be an economic incentive in moving towards a risk-based approach in that different options which are estimated to be ‘equivalent’ in terms of risk may be compared in terms of money. In principle, the cheapest option may then be adopted unless there is a good reason not to.

For these reasons a general shift is coming about to incorporate risk assessment as part of the overall design or operation of facilities in the built environment. An advantage of an approach which includes risk assessment is that, in principle, risks are looked for explicitly and considered. How to integrate fire safety considerations into architectural design has been addressed in [Cerda, M., 1981]. The point has been made [Wilson, C.B., 1978] that considerations of risk require something of a paradigm shift in thinking for a designer who, for an overall design,
is usually centred on the core objectives of the facility; ie, in the case of tunnels, underground transport of people and goods.

In a generic sense the essence of a risk assessment is to address the three basic categories:

- Hazard Identification. This centres on attempting to find answers to the basic question: what could possibly happen within this system which may lead to harm?
- Risk Analysis. This centres on attempting to identify and describe possible consequences.
- Risk Evaluation. This centres on deciding what, if anything, should be done to change the system.

The above would apply to both an existing tunnel system, e.g. up-grading, or to a tunnel system which exists on the drawing board, i.e. at the design stage. In a generic sense the above categories would also apply to a tunnel system in the construction phase; i.e. before the start of operation. Indeed, generically, the above categorization could apply to other types of risks as well, e.g. financial or environmental.

(It should be pointed out here that there is a lack of uniformity in the use of terms in risk assessment; different people and organizations use different terms in different ways. For example, the words ‘hazard’ and ‘risk’ are used in different ways; some use the word ‘hazard’, to the exclusion of the term ‘risk’ altogether and some vice versa. It is hoped that the publication of *The Handbook of Tunnel Fire Safety* [Beard, A. N.; Carvel, R.O., 2005] will start to establish a uniformity in the use of terms. Certainly it would be desirable for commonality in the use of terms to come about.)

Considering safety risk, ‘harm’ in the above is generally taken to imply:

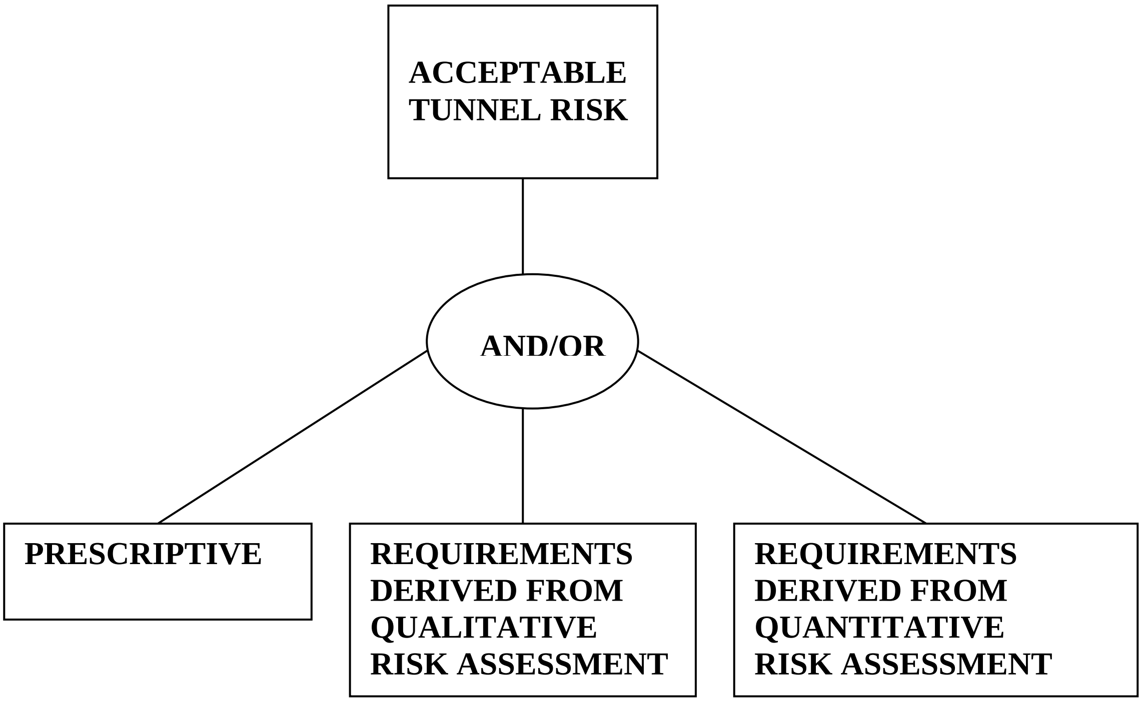
- Life loss or injury,
- Property damage,
- Disruption of operation.

Of these, prevention of life loss or injury may be regarded as the primary aim and avoidance of property damage or disruption of operation as secondary aims. In addition, there may be other considerations such as: political repercussions; loss of reputation; economic repercussions, other than implied in the primary or secondary aims; and social effects.

In relation to tunnel safety, specific pressures spurring a move towards an approach which includes risk assessment are being provided by the European Union via the EU Directive on road tunnels, 2004 and, significantly, by the global insurance industry via a code of practice for tunnel construction, described and discussed in [Dix, A., 2004].

In principle a new tunnel may be designed, or an existing tunnel up-graded, to produce an acceptable risk through the employment of prescriptive regulations or qualitative risk assessment or quantitative risk assessment; or a mixture of these approaches. This is expressed in Figure 6. Quantitative risk assessment may then be composed of deterministic risk assessment (i.e. using deterministic models) or non-deterministic risk assessment, or a mixture of the two (Physical models may also be used.)

Figure 6: Achieving acceptable tunnel risk



Several issues emerge when shifting to an approach to design which includes risk assessment:

(1) Which methodology should be used to address the three primary categories identified above? What are to be the criteria for acceptability of a methodology?

(2) Which models should be employed, and how, to assess the risk and make a decision? What are to be the criteria for acceptability of a model and how it is used?

(3) What are to be the criteria for acceptability of risk? This is basically an ethical decision, not a technical one. As such the criteria need to be generally acceptable to the public.

(4) To support the above a thorough knowledge and understanding of the system is needed; i.e. a ‘knowledge base’. This means there is a need for both theoretical and experimental research and gathering of information/data. Research needs to be on a continual basis because the real world system, and its values, changes.

Also, a desirable development would be the establishment of a ‘one stop shop’ for the EU which would act as a centre for the gathering of comprehensive information, e.g. statistical data on tunnel safety, as well as information about what research has been done and what is under-way. Such a ‘one stop shop’ would exist permanently and continually up-date its information base. It would serve as a very valuable resource for all those conducting tunnel safety risk assessments, as well as being available to other interested parties, e.g. operators, emergency services, regulators and other concerned parties.

In addition, it is necessary for a regulatory framework to be created which will allow acceptable models to be employed in a way which is generally acceptable to society.

3.3 Methodology for Design including Risk Assessment

In response to (1) above, different methodologies have been put forward, ranging from ‘hard’, e.g. [Open University, 1984] to ‘soft’, e.g. [Checkland, P.,1981]. A ‘hard’ methodology assumes the system is very well defined and a lot is known about it, as well as general agreement amongst the stakeholders. ‘Soft’ systems assume a lot of uncertainty and different viewpoints amongst stakeholders. Intermediate methodologies have been put forward, e.g. the implied methodology of the Health and Safety Executive (UK), [HSE, 2001], or those in [Hammer, R. W.; Miller, D. W., 1998], [Beard, 2005a] and [BSI, 2001]. Intermediate methodologies are likely to be the most appropriate for a human-technical system such as a tunnel. However it is important that a methodology not become a strait-jacket and that it be sufficiently comprehensive and flexible to allow different kinds of knowledge and experience to be incorporated in a systematic and coherent way [Beard, A. N., 2005; Beard, A. N., 2004].

To try to account for this, it is desirable for a methodology to have, at least, the following characteristics:

- The methodology should encourage the user to be explicit in what they are doing and make all assumptions crystal clear.
- Iteration needs to be included as part of the process.
- It should incorporate explicitly a capacity to learn from previous serious incidents. In the past this has often not been the case, [Vardy, A., 2001], [Drysdale, D., 2007; Buncefield, 2007].
- It should incorporate explicitly a capacity to learn from minor incidents or ‘near misses’, e.g. [Bodart, X. et al., 2004; Koornneef, F., 2000]. These represent a rich store of knowledge and experience which needs to be systematically tapped into. In the past this has been very far from the case.
- ‘Buried research’ needs to be brought to the surface and realized as part of risk assessment, [Beard, A. N., 2004].
- The methodology needs to be able to allow for different kinds of models to be employed, physical, qualitative and quantitative.
- ‘Precautionary’ and ‘Cautionary’ principles should be given due consideration.
- The former may be regarded as applying where it is unclear whether there is a significant ‘threat’ or not from some aspect (e.g. the introduction of a new material). The latter may be regarded as applying where there is certainly known to be a significant ‘threat’ from an aspect; this may be regarded as similar to the principle of applying a ‘safety factor’.

Such a concept might be applied to the process of risk assessment as well as directly to the tunnel system itself. The European Commission has published a document on the Precautionary Principle, [EC, 2000].

- Safety management system. For a risk assessment carried out as part of design, i.e. before the start of operation, then a safety management system (SMS) needs to be designed as part of the system being assessed on the drawing board. The SMS needs to be as 'systemic' as possible. After the start of operation, then a risk assessment needs to be conducted on a continual basis as part of the SMS. That is, in a sense, the situation becomes reversed.

A first pass through an acceptable methodology may be purely, or largely, qualitative. In the course of later iterations then quantification may be introduced. Iterations would continue until homeostasis has been reached, i.e. no new information is being introduced and no new insights are coming to the fore.

A possible generic methodology for design including risk assessment is given in Figure 7, taken from [Beard, A.N., 2005]. *In applying such a methodology the features identified in the bullet points above should be put into effect.* The methodology refers to the concept of 'Crucial Event'; for more on this see Section 3.6. A possible methodology has also recently been put forward by PIARC (the World Road Association), see Section 3.7.

Figure 7: A generic methodology for design including risk assessment (In applying such a methodology the features identified with the bullet points in Section 3.3 should be put into effect); copyright A. N. Beard

1. Formulation of the Problem

New or existing tunnel? Regulatory requirements.

↓

2. Hazard Identification

Finding answers to the question:
"What could possibly happen within this system which may lead to harm?"
Identification of Crucial Events and how they may come about.
Information from all sources may be used. Models of all kinds may be employed: verbal, mathematical and physical, as well as test results. Models employed may be qualitative alone or qualitative and quantitative. Quantitative models may be deterministic or non-deterministic.

↓

3. Risk Analysis

Identification of possible consequences of Crucial Events.
Comments in box 2 above about information and models apply here also.

↓

4. Risk Evaluation

Deciding what to do, if anything.
Generation of options to address the problem. Comparison with Criteria for Acceptability of Risk.
Choosing an option.

↓

5. Carrying out Action

↓

6. Appraisal

Keep cycling through the methodology until the end of the life of the tunnel. The 'problem' will change as time goes on; things are never 'closed' during the life of the tunnel.

3.4 Qualitative and Quantitative Models

In addressing point (2) of Section 3.2 above, different kinds of models may be employed in the process of addressing the three categories identified in Section 3.2. These are [Beard, A. N., 2005]:

(1) Qualitative models. These are verbal conceptual models based upon knowledge and experience. These may result from, for example, case studies of past incidents, or the experience of one or more persons, e.g. engineers, operators or fire brigade personnel. It may also include qualitative models (observations) resulting from physical models or historical data. There are also formal qualitative models such as Failure Modes and Effects Analysis (FMEA). (2) Quantitative models. These are physical models and theoretical models.

(2a) Physical models. These would correspond to experimental tests.

(2b) Theoretical models. These are deterministic models and non-deterministic models. Non-deterministic models include probabilistic models, statistical models and points schemes.

3.4.1 Quantitative Theoretical Models

More will be said about quantitative theoretical models here as these usually form a key part of a risk assessment. First, however, a few words of description are required:

Deterministic models: in essence, these predict values of given variables (e.g. temperature) as a time series i.e. at given times. Classic deterministic models are based on, for example, Newton's Laws. Non-deterministic models include:

Probabilistic models: these predict a range of possible outcomes.

Statistical models: these are non-deterministic models but do not employ the concept of probability.

Points schemes: these, also, are non-deterministic models; they are a way of distilling expert judgement. Essentially, points are assigned to various factors and combined to arrive at a single 'point' representing the risk implicit in the system. The EUROTAP model is an example of a points scheme; see Section 3.

3.4.2 Problems with Using Models

There are significant problems associated with using models as part of safety decision-making. These have been described and discussed in [Beard, A.N., 2005b], where many additional references are given. Many computer-based models exist today, for a survey of models, see [Olenick, S. M.; Carpenter, D. J., 2003].

Uncertainty in Estimates of Risk

Uncertainties in risk analysis have been described in [Pate-Cornell, M. E., 1996] where "six levels" are identified. Uncertainty in deterministic modelling has been considered in [Lundin, J., 1999]. Also, sources of error involved in using models have been described in [Beard, A. N., 2005b] and the references contained therein. In summary these are:

(1) Lack of reality of the theoretical and numerical assumptions in the model;

(2) Lack of fidelity of the numerical solution techniques;

(3) Direct mistakes in software;

(4) Faults in the computer hardware;

(5) Mistakes in application (i.e. 'simple' mistakes, such as hitting a wrong key or mis-reading a number; this is distinct from inappropriate interpretation of results);

(6) Inadequate documentation.

In the above, {2}, {3} and {4} would only apply to computer-based models. For computer-based models in particular there is the problem that some commercial source codes are not generally available to the public in general or the scientific community in particular. This means that conceptual or numerical assumptions contained within the code cannot readily be examined by the international community. Beyond the above sources of uncertainty there is the problem of inappropriate use of a model and inappropriate interpretation of results.

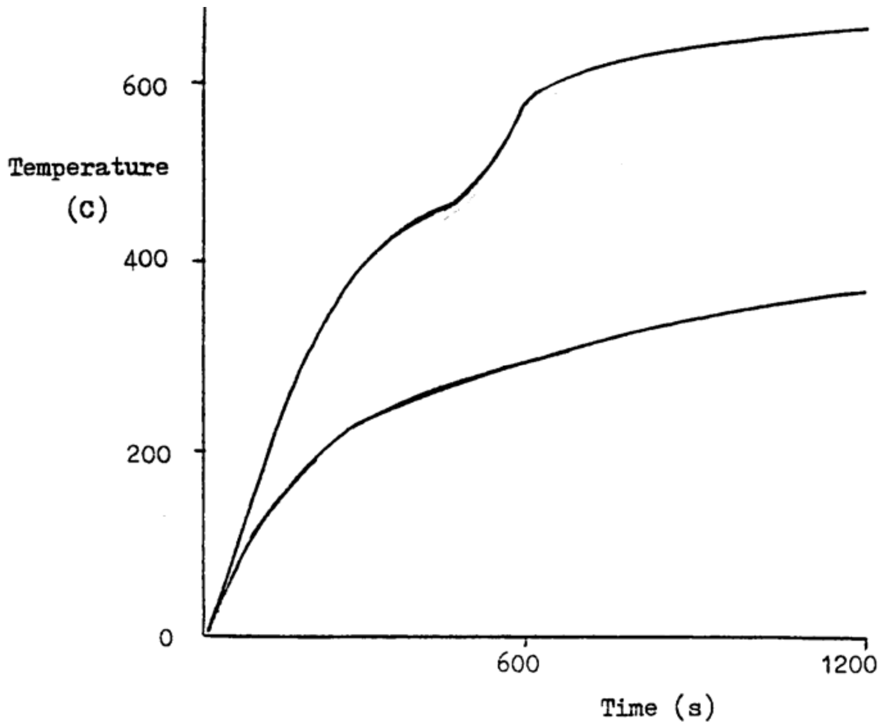
Testing of Models

Testing of models is problematic and has been discussed in [Beard, A. N., 2005b]. Deterministic models can, in principle, be compared with experiment. However, how the comparison is carried out is very important [op. cit.]. Also, it may be noted that experimental data are not necessarily 'hard and fast' but are subject to, for example, uncontrolled variables. Even experiments which are intended to be replications and should, in principle, produce identical results may not do. See Figure 8 which gives results from two tunnel experiments intended to be identical [Beard, A. N., 2005b].

Comparison between theory and experiment is not a straightforward process and different kinds of comparisons need to be carried out [Beard, A. N., 2005b].

Probabilistic models cannot be directly compared with experiment and testing is more problematic. The only real test for a probabilistic model of a system is to compare with historical statistical data for the system of concern.

Figure 8: Ostensibly 'identical' tests; results from two experiments intended to be the same (copyright A. N. Beard)



Independence of Assessment of Risk

Given the many sources of error and bearing in mind the possibility of commercial or other pressures, it is important for a risk assessment to be conducted by a person who is as independent of the system under scrutiny as possible. Further, a risk assessment for a specific tunnel, once conducted, needs to be examined by a second independent person.

It is evident that the use of models as part of safety decision making has a potentiality to lead to unacceptable design. There may be considerable variability in results from using models.

Variability of Results

Different users may produce quite different results, even when using the same probabilistic models, the same data base and applying it to the same case. In a European study, relating to offshore platforms, referred to in [Hawker, C.R., 1995] it was found that risk estimates produced by different users differed by "several orders of magnitude". An order of magnitude implies a factor of ten. A similar point may be made about deterministic models. Different users may employ very different input in applying the same model to the same case, producing different results. Also, the knowledge and experience of the user becomes crucial.

Further, there may be considerable differences in results from applying different deterministic models, including computational fluid dynamics (CFD)-based models, to the same case. Different users, applying different deterministic models to the same case, may produce very different results. This was found in a 'round robin' exercise sponsored by the Conseil International du Batiment (CIB), i.e. the International Council for Building. Different groups were invited to model fire development for specific building cases, being given information about the cases but no results of fire tests conducted in those cases; [Hostikka, S.; Keski-Rahkonen, O., 1998]. In a similar, more recent, 'round robin' exercise involving different teams modelling a specific case it was found that "the results show considerable disparity…between themselves and also differing from the experimental data", [Rein, G. et al., 2007]. These two round robins relate to buildings rather than tunnels. However, modelling in relation to fires in buildings has been in existence for much longer than modelling of fires in tunnels.

The position in relation to tunnels would, therefore, be expected to be no better than that for buildings and probably worse. Also, in a study directly related to tunnels, see [Tuovinen, H., et al., 1996], significant differences were found by the same model user in applying two different CFD-based models to the same tunnel case. In general, for CFD-based models, the view has been advanced that "a high level of skill is required by users" [Rhodes, N., 2000].

This gives a flavour of the kinds of problems which exist in using models as part of safety decision-making. Further, this applies generally to the built environment, not just to tunnels.

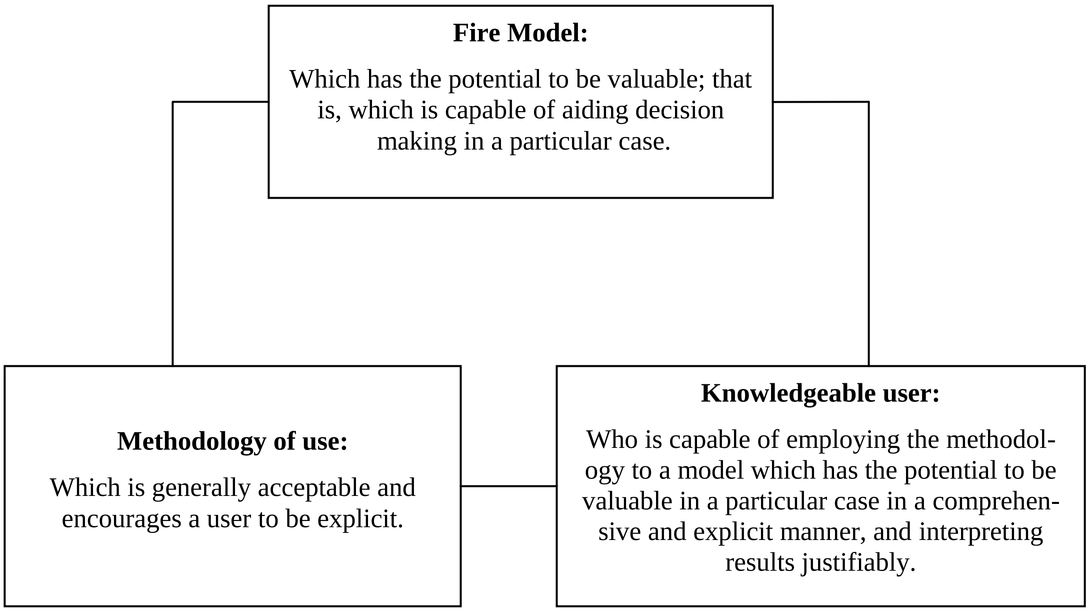
A regulatory framework needs to be created in order for models, especially computer-based models, to become generally acceptable as part of safety decision making.

Creating a framework which is acceptable to society as a whole is very important. An attempt to address the problems is encapsulated in the 'Fire Design Triangle' of Figure 9 [Beard, A. N., 2005b]. This figure refers to fire, but it would apply equally to safety as a whole. In Figure 9, the corners of the triangle represent 'Fire Model', 'Methodology of Use' and 'Knowledgeable User'. The categories represented by the corners of the triangle are interdependent; they will be described briefly and the implications pointed out:

(1) *Fire Model: which has the potential to be valuable; that is, which is capable of aiding decision-making in a particular case.*

While the term ‘fire model’ is often used to imply a deterministic model, it should be seen generally to include deterministic, probabilistic, or other models. Further, it should be taken to include evacuation modelling as well as fire development. All models make assumptions, both conceptual and numerical, and these may or may not be very realistic. Further, all computer-based models use numerical solvers and these contain further assumptions. The limitations and conditions of applicability of a model need to be determined and set forward in an explicit way.

Figure 9: Fire Design Triangle (May apply equally to non-fire). Basic requirements for acceptable use of a model as part of safety design. (copyright A. N. Beard)



Further, some computer source codes are not available for inspection or are available for inspection by a restricted number of users upon payment of relatively large sums of money [Beard, A. N., 1992]; this is especially the case for commercial packages. This is unacceptable for two reasons: {1} it breaches a fundamental principle of science, i.e. open-ness to scrutiny by the public in general and the scientific community in particular (assumptions may be ‘hidden’ in the code, as has been found in the past), {2} public safety may be compromised unnecessarily if computer codes are employed in decision-making and those codes are not open to scrutiny by the public in general and the scientific community in particular. As an example [Beard, A. N., 1992a], a CFD model was found to give results which were insensitive to values of a wall ‘smoothness factor’; this may have been interpreted as an insensitivity in the real world. However, an inspection of the computer source code revealed that this was a numerical device employed in the code, not a result of the physics of the situation. This had not been apparent from the documentation and may have led to false interpretation. Generally, computer source codes are not available to users.

Probably most models have the potential to be valuable, in one way or another, in some cases; that is, are capable of aiding decision making. Sometimes, however, it is difficult to see how a given model may be of value. For example, it is difficult to see how a typical deterministic control volume model could be of value in relation to irregular geometries.

To take a particular case, while computational fluid dynamics (CFD) models were used in a valuable way (see [Simcox, S. et al., 1988] and [Cox, G. et al., 1989]) in modelling fire development up an escalator in the investigation after the King's Cross Underground Station, London, fire of 1987, use of a typical zone model would have been inappropriate.

As another, general, example; a model may be relatively 'realistic' in a qualitative way in a particular application (in the sense of indicating trends) but may be poor quantitatively. (For more on model types, see [Beard, A. N.; Carvel, R. O., 2005].)

This implies: a need for independent assessment of each model, examining both qualitative and quantitative aspects; acceptable methodologies for assessment need to be devised.

It implies, in addition: the need for the existence of one or more independent Model Assessment Groups (MAGs) which would produce written assessments on models.

Independent assessments need to be carried out on a rational, comprehensive, basis with justifiable conclusions. This would include considerations of the limitations and conditions of applicability. In this respect the assumptions in a model, per se, would need to be clearly differentiated from the assumptions which might be made in a particular application. These assessments of models would be updated and would act as a resource for regulatory bodies and 'knowledgeable users'.

Also, this implies the need for an Approvals Body which would approve the use of a model for 'real-world' use under given conditions, including the use of an acceptable 'methodology of use' by a 'knowledgeable user'.

It is essential, however, to realize that 'approval' would not be for a model as such. It would imply approval *under given conditions and given an acceptable methodology of use by a knowledgeable user*. The corners of the design triangle are inter-connected and it needs to be seen as a whole. Simply 'approving' a model per se would be undesirable as it may imply that if a particular model is used then a risk assessment using it would be acceptable, which would not necessarily be the case.

Such an approvals mechanism would operate at both a general level and at the level of a particular case. At the 'particular case' level it would be expected to interact strongly with local regulatory bodies such as building control offices and fire brigades in the U.K. The Approvals Body would call upon the reports of MAGs and any other relevant information. It is not adequate to rely solely on fragmented local reaction; regulators (i.e. fire brigades/building control officers etc) need help. All related documentation would, as above, act as a resource for regulators and 'knowledgeable users'.

It may be argued that the creation of independent MAGs would be difficult and that is no doubt true. However if independent assessments do not take place then it would mean that only 'non-independent' assessments could be expected to exist. By definition that would mean that only 'biased' assessments were available. A non-independent or 'biased' assessment would not necessarily be of no value; indeed non-independent assessments can provide very useful information. However, the value of such an assessment is circumscribed. Independent assessments are needed in addition. If models are to become a significant part of design then there must be a place for independent assessment, based on a rational and comprehensive
approach and with justifiable conclusions. A sketch of a possible generic procedure for carrying out an assessment for a deterministic model is given in [Beard, A. N., 2005c]. Specific procedures would be necessary for different kinds of models.

It is not possible to carry out a truly ‘independent’ assessment, there will always be partiality to some degree or other; we all have our own views, knowledge, experience and interests. However, in this context, ‘independent’ may be taken to mean that those conducting an assessment do not have an interest in seeing a particular model portrayed as either ‘good’ or ‘bad’. In that sense it is possible to conceive of an independent assessment and such independent assessment of models is not only possible but necessary.

Assessment of a model by those who have an interest in seeing it portrayed as either ‘good’ or ‘bad’ is of limited help in real-world applications. It is often not impossible to create an assessment of a model which has conclusions which are favourable (or unfavourable) to a particular model, depending upon how the assessment is conducted.

For example, because of uncertainty in input and flexibility in method of application, the choice of parameter values and experimental data for comparison gives scope for finding a favourable or unfavourable comparison if that is, either consciously or unconsciously, desired. In an age of commercial computer packages this problem becomes even more acute.

(2) *Methodology of Use: which is generally acceptable and encourages a user to be explicit.*

How a model is used as part of a given application is of vital importance. It is very easy to use a model in a naïve and unjustifiable way. For example, the assumptions made in a particular application (as distinct from the assumptions made in the model per se) need to be clearly set down. That is, how the particular application is ‘idealized’ in the use of the model in a particular case certainly affects results and conclusions. How uncertainty in the input is considered, the choice of parameter values, the degree and nature of any sensitivity considerations etc will affect results and conclusions. Methodologies are required, the stages of which encourage a user to be explicit about what has been assumed and done in the application. A generic ‘methodology of use’ for a deterministic model is suggested in [Beard, A.N., 2005c]. Such methodologies need to be devised for different types of models. Other material relevant to this is included in references [Kumar, S., 2004] and [Kumar, S.; Cox, G., 2001].

A similar situation arose in the case of finite element models and structural analysis. This led to a project which resulted in the SAFESA (safety critical structural analysis) methodology; [Morris, A. J., 1993; SAFESA, 1999]. That methodology, through its stages, encourages a user to be comprehensive and explicit about what they are doing and the assumptions made in a given application. Overall, the implication is: similar projects are needed to construct acceptable methodologies of use for models used as part of tunnel safety decision-making.

However, it would be quite possible for an acceptable methodology of use to be applied to a model which had the potential to be valuable, but in an unacceptable way. An acceptable methodology of use needs to be applied by a ‘knowledgeable user’ and this brings us to the next section.

(3) *Knowledgeable User: who is capable of employing an acceptable methodology of use to a model which has the potential to be valuable in a particular case in a comprehensive and explicit manner; and interpreting results justifiably.*

This implies: creating people who have knowledge of both the relevant science and detailed knowledge of a model being used. A ‘registration council’, or similar, might be set up to ‘register’ particular users in relation to particular models, particular ‘methodologies of use’ and model uses. It further implies having educational courses which can help to do this. Such courses may be used to ‘register’ particular users. Educational institutions providing such courses should not have an interest in portraying a particular model or methodology as either ‘good’ or ‘bad’.

There is a need to create a sufficient number of ‘knowledgeable users’; however, ‘knowledgeable use’ and justifiable interpretation depends on experience, not just ‘education’. ‘Registration’ of a user could not guarantee ‘knowledgeable use’; however, it is hoped that it would *help* in the creation of ‘knowledgeable users’. It is important, therefore, for all those with relevant ‘on the ground’ knowledge and experience, e.g. operators, fire brigade personnel, to be involved when models are being used and results interpreted.

Models should only ever be used in a supportive role and not as a sole basis for decision-making.

Initiatives by specific organizations have already resulted in documents related to this area; for example, the documents of the Model Evaluation Group of the European Union [EC, 1994] and the American Society for Testing and Materials standard for evaluating deterministic fire models [ASTM, 1997]. There is also a standard from the International Standards Organization, incorporated into British Standards, [BS ISO, 1999].

Further, there is also some guidance which resulted from the *Workshop on the Development of Key Performance Indicators for the Use of Computer Models in Support of Fire Safety Engineering*, held at the Building Research Establishment, UK in 2003; i.e. [Kumar, S.,2004]. Thus far, however, there is no generally acceptable, comprehensive, coherent, regulatory framework for the acceptable use of models as part of safety decision-making. It is necessary for one to be created.

3.5 Criteria for Acceptability of Risk

To follow up point (3) in Section 3.2 above; deciding on the criteria for acceptability of risk is fundamentally an ethical issue, not a technical one. As such, it should be generally acceptable to the public as a whole and decided by the political representatives of the public.

Different indicators of risk may be used. These may be expressed as deterministic or non-deterministic indicators. Different criteria for acceptability of risk may then be specified for each.

Deterministic criteria may specify, for example, acceptable levels of temperature or toxic gas concentrations.

For non-deterministic criteria, currently the most used indicators are frequency, probability or ‘points’ in a ‘points scheme’. An example of a points scheme approach is given by the EUROTAP, [EUROTAP, 2006], scheme to be described later; run through the German automobile organization ADAC. However, the principal non-deterministic indicators are:

- Frequency: e.g. the number of fatalities ‘per person km’ or ‘per vehicle km’ or, simply, ‘per km’.
- Probability: e.g. the probability of a person being killed per year.

Such indicators, or measures, may be applied to particular categories of people, eg, in the case of railways: (a) all types of people; (b) all passengers; (c) a particular sub-category of passengers, e.g. ’a regular user’; (d) train crew; (e) staff other than train crew.

Beyond that, the two kinds of risk generally considered are:

- Individual risk: this would be the risk to a member of a specified group of people, such as one of the categories above. For example, a worker or a member of the public who is a ‘regular user’. Such categories are open to interpretation as to how they may be defined.

- Societal risk: this is the risk to society 'as a whole'. It is generally interpreted in terms of frequencies of incidents with multiple fatalities and described mathematically as a 'F-N' curve; where F is the frequency of an incident involving N or more fatalities. The greater is N then the smaller is the acceptable frequency.

Similar risk measures may be used for people living in the vicinity of a tunnel, rather than people who are directly connected with a tunnel such as travellers or staff.

Both deterministic and non-deterministic approaches are allowed in guidance on the employment of the techniques of fire safety engineering in building design in the UK, see [BSI, 2001].

In that guidance the option of designing by using deterministic models alone is allowed and deterministic criteria for acceptability of risk are used. For example, the intention may be to design to a maximum allowable radiative heat flux or toxic gas concentration. Values of such variables would be estimated using deterministic models, such as CFD-based models or control volume models. The main point is that the criteria are expressed deterministically.

In the guidance it is also allowed to adopt a probabilistic approach and in this case probabilistic criteria need to be decided upon. In this respect an approach similar to that adopted by the UK Health and Safety Executive and described in [HSE, 2001] has started to become employed in different countries; e.g. Norway, [Musaeus, S.U, 2004] and the Netherlands [Worm, E. W., 1998]. This approach is encapsulated in the 'Risk Carrot' diagram of Figure 10. This approach is also known as the 'ALARP approach' or, more broadly, the 'Tolerability of Risk (TOR)' approach. ALARP is an acronym for 'As Low As Reasonably Practicable' and the HSE sees it as a part of the overall TOR approach. The essence of the approach is to specify a level of risk for a member of a specified group (i.e. worker, member of the public) above which the risk is unacceptable. The current guidance for this level is for the risk of fatality per year to be 10^{-3} (1 in 1000) for a worker and 10^{-4} (1 in 10000) for a member of the public. For risks which are estimated to be less than a specified level, 10^{-6}; i.e. 1 in 1 million in the HSE approach, the risk is regarded as not requiring much attention, unless improvements can be made at relatively low cost.

Between these two levels the risk is regarded as 'Tolerable' but efforts should be made to reduce the level below the 'Unacceptable' level as much as possible, essentially, using cost-benefit analysis. For a cost benefit analysis then it is necessary to assign a 'Monetary Value of a life' or 'Value to prevent a fatality (VPF)'. Some implied values used in different countries at 1998 prices, in US dollars, are given in Table 2, see [Diamantidis, D., 2002].

It is seen that very different values have been used in different countries. The VPF values used have also depended on the nature of the risk, for example, more money may have been spent to prevent a fatality in a particular case on the railways than in a particular case on the roads. In 2001 the HSE in the UK set a guideline value for the VPF at about £1m (approx. 1.5m EUR). Different values have been adopted for different cases. For example, for the proposed Stonehenge Tunnel (road) in the UK a value of approximately £1.3m (1.95m EUR) has been adopted. In the Channel Tunnel Safety Case, [Channel Tunnel, 1994], "some few millions of Pounds Sterling" is referred to as the maximum cost of avoiding a fatality (See, also, the Channel Tunnel Rail Link, Section 6).

It was concluded in the Safety Case for the Channel Tunnel that "passengers will be at least 20 times safer travelling through the tunnel than travelling by conventional railways". Given subsequent events, the plausibility of the original risk estimate, especially the fire risk estimate, must be called into question. In overall terms the criterion for the Channel Tunnel, as set down by the Channel Tunnel Safety Authority, was:

"A passenger travelling by train from London to Paris should be in the part of the journey through the Tunnel at least as safe as in the equivalent length of the journey (i.e. 50 km) from either Waterloo to Folkestone or from Sangatte to Paris". Similar, although subtly different, criteria have been adopted in other cases, e.g. the Oresund link between Denmark and Sweden, [Andersen, L. W., 1998].

Table 2: Some implied values used in different countries for the Value to Prevent a Fatality (VPF)

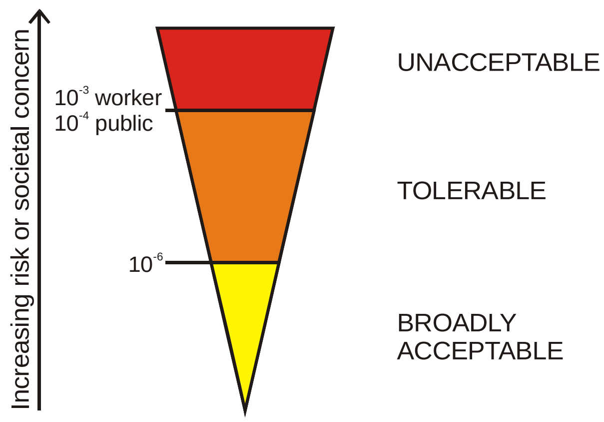
Country	VPF (Million USD, 1998 prices)
Germany	4.2
Sweden	3.85
Australia	3.07
UK	2.74
Japan	5.9
USA	4.06

In the application of cost benefit analysis, the HSE makes the point that it should be interpreted in light of the 'Edwards vs NCB' legal case of 1949, [HSE, 2001]. That is, that a measure should be put into effect unless there is a "gross disproportion" between cost and benefit. That is, effectively, a measure or option should be adopted unless the estimated cost is 'grossly' greater than the estimated benefit.

It should also be noted that an important part of the HSE approach is to consider 'societal concerns'. It can be seen that, in Figure 10, the vertical axis is 'increasing risk or societal concern'. That is qualitative social considerations may, in the final analysis, over-rule quantitative considerations. More generally, concerns have been expressed about the use of cost benefit analysis [Adams, J., 1995]; for example, what is to be included as a 'cost' and what a 'benefit'?

Different values which have been put forward for the maximum tolerable risk for different countries and some are given in Table 3. In the case of tunnels, as an example, the upper and lower limits as given in Table 4, were used for the West Rail Tai Lam tunnel, Hong Kong, [Lupton, B., 1998]. In Table 4 the individual risk is based upon the most exposed member of a particular group. For passengers, for example, this is taken to correspond to a 'regular commuter' and this has been assumed to correspond to 600 journeys per year.

Figure 10: The 'Risk Carrot' of the UK Health & Safety Executive, [HSE, 2001] (Numbers refer to probability of fatality per year)



In recent years the HSE has become very concerned about the uncertainty involved in using theoretical models and it appears to be the case that less emphasis is being placed upon the numbers than in the past. This view has been expressed in relation to both the oil and gas industry and tunnels.

Concern about uncertainty is a good reason for there to be a healthy mix of qualitative and quantitative in risk assessment and in decision-making. Precisely what a ‘healthy mix’ might consist of is a matter for discussion.

Table 3: Individual Risk Criteria for Different Countries (Fatality)

Country	*Description*	*Criterion (per yr))*
U.K. (HSE)	Maximum tolerable risk to workers	10^{-3}
	Maximum tolerable risk to public	10^{-4}
	Broadly acceptable	10^{-6}
Netherlands	Maximum tolerable risk for existing situations	10^{-5}
	Maximum tolerable risk for new situations	10^{-6}
Western Australia	Sensitive developments (hospitals, schools etc)	$5 (10^{-7})$
	Residential zones	10^{-6}
	Non-industrial (commercial, sporting etc)	10^{-5}
	Industrial	$5 (10^{-6})$

Table 4: Individual risk criteria for the West Rail Tai Lam Tunnel, Hong Kong (Probability of fatality per year; 10^{-4} equals 1/10000 and similar)

Exposed Group	*Staff*	*Staff*	*Passenger*	*Passenger*	*Public*	*Public*
Total for all hazards	Upper	Lower	Upper	Lower	Upper	Lower
	10^{-4}	10^{-7}	10^{-5}	10^{-7}	10^{-5}	10^{-7}

Sometimes, for tunnels, individual risk is measured as ‘the number of fatalities per 100 million transits’, or similar. As an example, The upper levels of the individual risk criteria for the Channel Tunnel are given in Table 5. The chance of being killed of 1 in 1000 per year for the most exposed workers is based upon the HSE criterion; which is similar to the risk for the most exposed workers in the British and French (SNCF) networks.

Table 5: Individual Risk Criteria for the Channel Tunnel; fatality frequency

Personnel Group	Upper Level of Tolerable Risk
Shuttle passengers	5.6 per 100 million transits
Passenger train passengers	4.7 per 100 million transits
Passenger train crew*	26 per 100 million transits
Freight train crew**	31 per 100 million transits
Eurotunnel staff	1 in 1000 per year

* Based on 24.5 mins within the tunnel system

** Based on 30 mins within the tunnel system

Different criteria have been chosen for different groups. It is even the case that different criteria have been adopted for different passenger categories; i.e. shuttle and train. It may be noted that 4.7 fatalities per 100 million transits converts to approximately 0.8 per billion person km; total length = 58.5 km. This includes passenger accidents other than at stations as well as 'train accidents' such as fire, collision or derailment. For the Oresund Link between Denmark and Sweden the criterion for acceptability of risk was stated as "shall be comparable with other similar traffic installations", [Andersen, L. W. et al., 1998]. This was interpreted as the average fatality risk on Danish and Swedish motorways and railways. The Oresund Link figure for railways below appears to be based on 'train accidents' as indicated above.

The numbers in Table 6 are such that the risk on the Link is to be "comparable", they are not necessarily an 'upper tolerable limit' in the sense of the ALARP approach. Also, the Oresund criterion applies to the entire 16 km Link, not just the 4 km tunnel part. This serves to illustrate the difficulties of comparison between cases often experienced.

Different criteria are also generally adopted for road and rail; as seen, for example, in Table 6 see (Andersen, L. W. et al., 1998).

Overall, it is the case that different criteria have been used in different cases. It needs to be decided whether it is ethically acceptable to adopt different criteria for acceptability of risk in different cases; especially for road and rail tunnels.

Table 6: Implied Individual Risk Criteria for the Oresund Link; i.e. implied levels for which the risk on the Link should be "comparable" to be acceptable

Transport mode	*Fatalities per 1 billion passages for a stretch of 16 km i.e. the total length of the Link (per billion person km in brackets)*
Road	33 (2.06)
Rail	4 (0.25)

A question which emerges from such considerations is: if the same criteria for acceptability of risk were adopted across the EU, would all countries be able to afford the implied costs, assuming a 'high' standard was adopted? There may be pressure to adopt a 'low' standard across the EU because of this.

The 'ALARP approach' has been used in countries other than the UK, for example the Netherlands [Worm, E. W.; Hoeskma, J., 1998] and Norway, [Musaeus, S. U. et al., 2004]. However, in Norway they have coupled the 'ALARP' approach with a 'Vision Zero' policy; see below. Denmark and Sweden have similar policies.

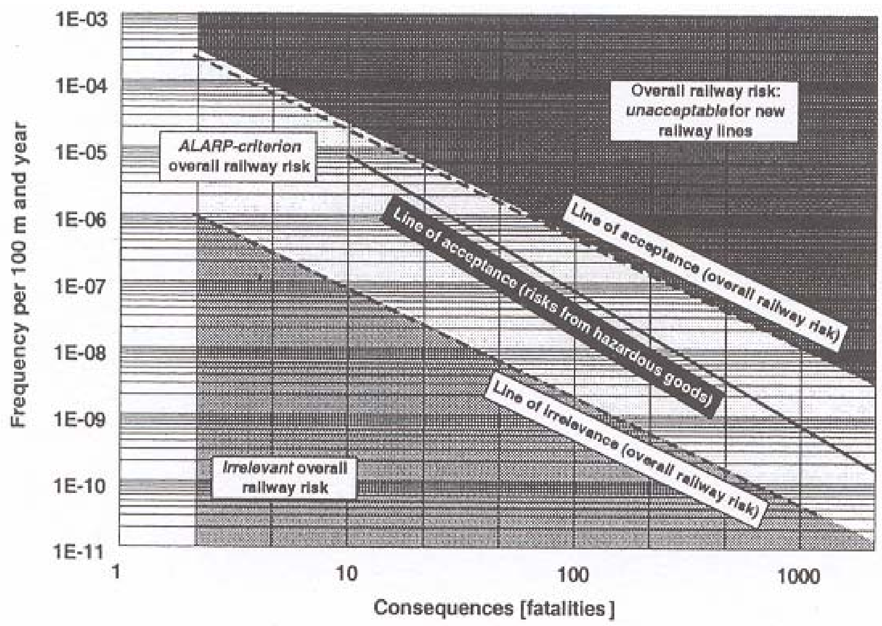
Multiple Fatalities

As mentioned above (Section 3.5) the 'societal risk' is generally measured via a 'F-N' curve, indicating frequencies of fatalities for different numbers of deaths in a single incident. Curves are generally represented as straight lines on logarithmic paper. As examples, the 'Intolerable Limit' curve for the Channel Tunnel is indicated by the data in Table 7:

Table 7: Channel Tunnel: Points indicating 'Intolerable Limit' on a F-N curve.

Number of fatalities	*Frequency per year km*
N = 10	2.2 (10^{-4})
N = 100	1.8 (10^{-5})

Figure 11: Societal Risk Criteria for the Gotthard Base Tunnel (F-N Curves) (Note: 1E-03 means $1(10^{-3})$ i.e. 1/1000 and likewise)



By comparison, the "Line of acceptance (overall railway risk)" for the Gotthard Base Tunnel, which is currently being constructed in Switzerland, is indicated in Figure 11, [Gerber, P., 2001]. This figure shows three F-N lines (i.e. 'curves'): the upper limit above which an option is unacceptable, a lower limit below which an option is certainly acceptable and the region between, i.e. the ALARP region, see Section 6. Between these two lines is a line indicating the "Line of acceptance" for risks from "hazardous goods". It should be noted that the frequencies on this figure are "per 100m and per year" whereas in Table 7 the frequencies are per km and per year. It appears that the 'intolerable frequency' at N = 10 on Figure 9 is very approximately the same as the equivalent frequency in Table 7, although the frequency on Figure 11 for N = 100 seems to be lower than the equivalent frequency in Table 7.

The essential point is that different criteria for societal risk (i.e. F-N curves) are used in different cases. In general there is a lack of consistency.

Multiple Fatality Risk Aversion (MFRA)

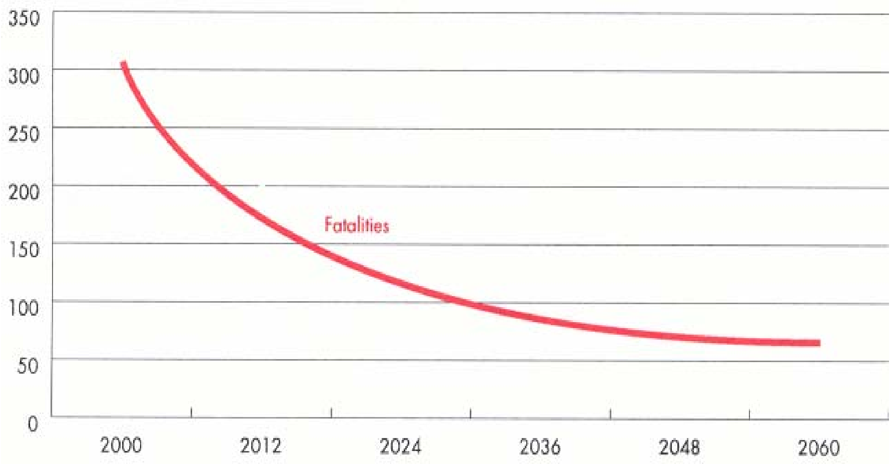
Whether or not a MFRA is to be applied has to be decided. That is whether, for example, one incident with ten fatalities is to be regarded as 'worse' than ten incidents each with one fatality in the same period. (This manifests itself as the gradient of a curve on a F-N diagram.) For one case of a tunnel in the UK the proposed criteria did not apply a MFRA factor, [Trbojevic, V., 2003]. For another tunnel, in the Netherlands, a MFRA factor was applied, [Worm, E. W.; Hoeskma, J., 1998]. Whether or not to apply a MFRA factor is a matter with direct ethical, social and political dimensions and as such needs to be decided by the representatives of those who travel through tunnels, i.e. of the public.

Vision Zero

The Norwegian Government has adopted a 'Vision Zero' policy which has been stated as [NPRA, 2006]: "The Government views the large number of killed and injured in road traffic as a serious national concern. Therefore, a vision of no one being killed or permanently disabled has been established as a basis for the long-term traffic safety effort. The vision means that the Government, in addition to conducting a policy with the goal of reducing the total number of accidents, will focus strongly on measures that can reduce the most serious accidents."

The reduction in fatalities anticipated is shown in a graph, see Figure 12. Sweden and Denmark also have 'Vision Zero' policies.

Figure 12: The Norwegian Vision Zero Curve (fatalities/year)



Whether or not a 'Vision Zero' policy should be adopted across the European Union is a matter which needs to be decided. A strategy would need to be adopted to ensure that genuine reductions in risk were actually occurring, over time, 'on the ground'. Historically, because 'the system changes' risk has often tended to increase in a given tunnel (e.g. because of road traffic changes). An increase in risk appears to have a tendency to 'creep up' on us. This is an example of the 'boiled frog' syndrome, [Senge, P.M., 1993], in which a frog, sitting in a pan of initially cold water, does not notice that the water is gradually heating up until it is too late. An awareness of this would need to be taken account of in a strategy. Also, it has been argued that human-technical systems have a general tendency for their 'entropy' (i.e. 'degree of disorder') to increase over time [Critchley, O.H., 1988]; *inter alia*, this links to the importance of maintenance. If this is the case then a 'double vigilance' is required at all levels, from the strategic level to the level of every-day operations.

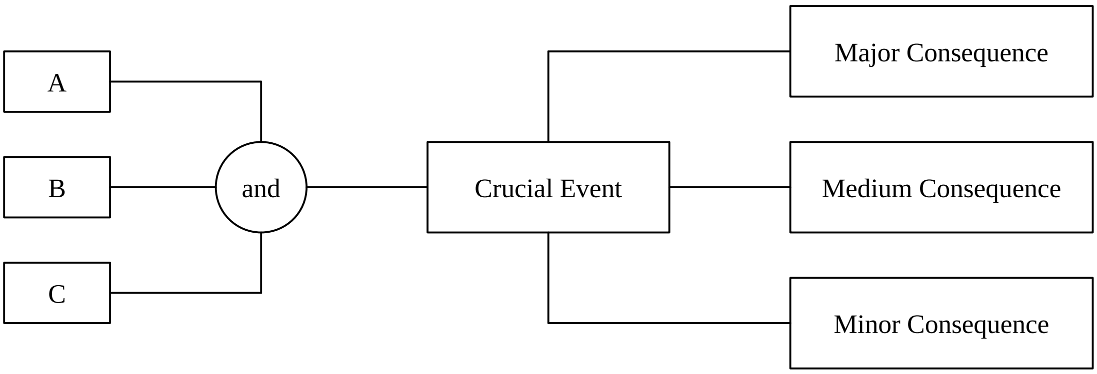
In Japan it appears to be the case that, generally throughout society, the only 'acceptable' level of risk has been zero, although there do seem to be some cases for which a non-zero acceptable level of risk, or "risk allowance", has been "officially stipulated", [Nakanishi, T., et al., 2003]. It seems evident that cost-benefit analysis is, at least sometimes, employed in Japan as shown by the figure which has been employed for the value of a life in Table 2.

3.6 Safety Management System

A comprehensive, coherent and dynamic safety management system is essential to tunnel safety. A design for the safety management system needs to be considered as part of a methodology for conducting a risk assessment. After a tunnel is operational then the situation becomes reversed and a continual risk assessment needs to be carried out as part of the safety management system. Safety management may be regarded as centred on the key concepts of prevention and protection. As with the words 'hazard' and 'risk' there is often lack of clarity in the use of these terms; a measure which one person refers to as 'prevention' another may refer to as 'protection'. However, greater clarity may be achieved by defining these terms in relation to the concept of a 'crucial event', which is "an event which may lead to harm", [Beard, A.N., 2005d]; see Figure 13.

A crucial event may be, for example, ‘ignition’. Measures which reduce the chance of a crucial event (CE) are preventive and those which help to protect after a crucial event are protective. (‘Protection’ here may be taken to include ‘total protection’, i.e. no harm occurs and ‘ mitigation’, i.e. ‘partial protection’ in which some harm would come about.) ‘Crucial’ comes from the Latin ‘crucis’ (a cross) and serves to emphasise the ‘crossing’ nature of the event; what happens before the CE is just as important, if not more so, than what happens after the CE. Identification of crucial events is an important part of a risk assessment. Many of the models used in risk assessment, especially deterministic models, start from the CE. Much better understanding and modelling of what happens *before* a CE is necessary. A coherent mix of prevention and protection so as to produce an acceptable system as a whole is at the heart of good safety management. (It may be noted that the recent EU Directive on road tunnels, [EU Directive, 2004], implies use of the concept of a crucial event, but calls it a ‘critical event’; although it does not define the word. However, the word ‘crucial’ is preferable to ‘critical’ in this context not only because it emphasises the crossing nature of the event but because the word ‘critical’ is used in many other contexts, including different ways within safety science. For example, it is used in relation to the ‘critical’ velocity to prevent backlayering of smoke and in the FMECA risk assessment technique i.e. ‘Failure Modes, Effects and Criticality Analysis’. Use of ‘crucial’ in relation to prevention and protection aids clarity and is conceptually preferable to ‘critical’.)

Figure 13: ‘Crucial Event’, illustrating Prevention and Protection



Models for safety management systems have been put forward by many organizations over the years and these have been studied by Santos-Reyes [Santos-Reyes, J., 2001; Santos-Reyes, J.; Beard, A. N., 2002]. A model for a ‘systemic’ safety management system has been put forward for tunnels and is described in [Santos-Reyes, J.; Beard, A. N., 2005]. This centres on a unit consisting of five key systems and their interconnections; ideally, the unit exists at different inter-connected levels, from the international or European level to the level of the individual tunnel. The five key systems are:

System 1: Tunnel safety policy implementation

System 2: Tunnel safety co-ordination

System 3: Tunnel safety functional; essentially the ‘inside and now’ system. This is responsible, *inter alia*, for day to day risk assessment.

System 4: Tunnel safety development; essentially, the ‘outside and future’ system. This is responsible, *inter alia*, for research and development and looking for changes to the system as a whole and the environment within which it finds itself.

System 5: Tunnel safety policy; responsible for strategic decision-making.

A unit consisting of systems 2-5 is referred to as a 'management unit'

If risk assessment is to be made common or harmonized throughout Europe then such systems might be established on a coherent basis at a European level. In particular, the establishment of a Europe-wide 'System 4' would be a desirable development. Such a system would, as part of its remit, look for 'outside and future' changes which may affect tunnel safety, for e-xample, changes in traffic patterns or vehicle construction. Changes in vehicle construction might include the tendency to have larger fuel tanks in HGVs because of different fuel costs throughout Europe and the move to hydrogen powered vehicles. Already there are hydrogen powered buses running on the streets of London and, seemingly, there is no restriction on their going through tunnels; at least that appears to have been the case in October 2006. However, there are serious questions about the risks posed by hydrogen powered vehicles, see [Wu, Y, 2007]. These are some of the issues which a Europe-wide System 4 might bring to light and, particularly, to the attention of those who need to know. Such a system would have a strong connection to an organization concerned with the 'knowledge/practice interface' and a 'one stop shop' for designers, regulators, emergency services and any others interested; see Section 3.7.

3.7 The Knowledge Base

In addressing point (4) of Section 3.2 above, knowledge, from historical statistics to in-depth conceptual understanding is necessary to sustain a safety decision-making approach which includes risk assessment. Both empirical and theoretical knowledge is required. Areas requiring much more knowledge have been identified in [Dix, A, 2005] and [Beard, A.N., 2005a]. We certainly know more about tunnel safety risk than we did twenty years ago. However, there is still a lot we do not know and, because the system changes, the research effort needs to go on continually. There is a link here to the concept of a 'System 4' as mentioned in the section above. Essentially, research is needed on the key direct components contributing to tunnel risk: Infrastructure; vehicles (including contents); operation (including incident response); human behaviour (both staff and travellers).

In the [EU Directive, 2004] some specific requirements may be regarded as not compulsory if a risk assessment shows that an alternative arrangement is equivalent in terms of safety. This means that we need acceptable models, used in an acceptable way, which are capable of relating *specific* measures (such as a specific ventilation system) to risk; in order to be able to demonstrate that two different systems are equivalent in terms of safety. As a general rule such models do not exist at the present time. Models created are often at a relatively high level of abstraction and are not able to reliably relate specific measures to the risk which emerges from the system as a whole. Adequate models, both deterministic and probabilistic, need to be created and independently assessed.

Research and Other Initiatives

Experimental tunnel fire tests have been described and reviewed in [Carvel, R. O.; Marlair, G., 2005a]. They make the points:

"In the early days of experimental tunnel fires, experiments were carried out with specific individual goals, e.g. to determine smoke behaviour under certain conditions. More recently there has been a trend to learn as much as possible from fire tests in tunnels and to this end there has been collaboration amongst several groups of people with different interests, best demonstrated by the EUREKA EU499 Firetun test series.

However, with the majority of tunnel fire experiments now being carried out by private companies, things appear to be reverting to the old ways again. This is a backward step which will tend to slow the rate of our advances in understanding fire behaviour in tunnels.

It is only through collaboration and publishing in the public domain that our knowledge of fire phenomena will be increased, and it is only through increased understanding that our tunnels can be made into safer places."

As well as this move towards private companies carrying out tunnel fire experiments to test their products, another consequence of the catastrophic tunnel fires in 1999 was the inception of a number of European Union (EU) funded initiatives to increase the safety and sustainability of the pan-European tunnel network. These initiatives are now described very briefly; all of them have now ended, [Brekelmans, J., 2003].

(1) **FIT** ('**F**ire **i**n **T**unnels'). Main objectives: dissemination of research results; establishment of databases; recommendations on design fire scenarios; guidelines for 'fire safe design'; 'best practices' for fire response management; see [FIT1, Haack, A.,]; [FIT2, Brousse, B.,]; [FIT3, Rhodes, N.]; these reports appear to be undated. In relation to this initiative it needs to be pointed out that because it has ended it is no longer possible for new people to register to gain access to the information.

(2) **UPTUN** (**Up**grading of **Tun**nels). This has been one of the most prominent initiatives. It focussed on the upgrading of existing tunnels [UPTUN, 2004]. The UPTUN consortium consisted of 41 members from 16 different EU Member States and an European Economic Area (EEA) Member State. This initiative also encouraged private companies to develop tunnel fire safety products. The main objectives of UPTUN were stated as:

- The development and assessment of innovative tunnel safety technologies.
  - The main focus on technologies in the areas of detection and monitoring, mitigating measures, influencing human response, and protection against structural damage.
  - The main output intended to be a set of innovative, sustainable, cost-effective technologies.
- The development, demonstration and promotion of procedures for risk level evaluation.
  - The main output, a risk-based evaluation and upgrading model.

The stated intended effects of the UPTUN project are:

- "The restoration of public faith in tunnels as safe parts of the transportation systems."
- "The levelling out of trade barriers imposed by supposedly unsafe tunnels."
- "An increased awareness of stakeholders for the necessity to develop initiatives to link all relevant research."

A document on risk assessment is due in the Autumn of 2007.

(3) **DARTS** ('**D**urable **a**nd **R**eliable **T**unnel **S**tructures'). Intended to develop 'cost-optimal' and durable new design.

(4) **SAFE-T** ('**Safe**ty in **T**unnels'). There are eight 'Work Packages, (WPs)' in this initiative and WP5 is concerned with 'Harmonized Risk Assessment'.

(5) **SAFE-TUNNEL.** Aimed at the development of preventive safety measures.

(6) **SIRTAKI** ('**S**afety **I**mprovement in **R**oad and Rail **T**unnels using **A**dvanced Information Technologies and **K**nowledge **I**ntensive Decision Support Models'). Aimed at tunnel management.

(7) **Virtual Fires**. Aimed at developing a tunnel fire simulator.

(8) **Tunnel Safety Awareness Campaign.**

In addition there is an on-going initiative supported by the German Federal Ministry of Economics and Technology: **SOLIT** ('Safety of Life in Tunnels') centred on evacuation, rescue and protection of the tunnel construction.

Beyond these initiatives it is vital that large-scale tests continue to be conducted as well as small-scale and laboratory-scale tests. Because of this, the move to establish a large-scale test facility in Europe is very important; i.e. **L-SURF**, 'Large-Scale Underground Research Facility'.

PIARC Initiatives

Work carried out under the aegis of PIARC (the World Road Association) has resulted in two reports: the first surveyed approaches and techniques which have been employed in different European countries, [PIARC, 2007] and the second put forward a methodology for decision-making in relation to road tunnel safety, [PIARC, 2007a]. This methodology is very similar to a methodology which resulted from the SAFE-T project mentioned above [SAFE-T, 2006]. These methodologies draw out the category "Educate Users" as an explicit part of the approach, although no other specific measures are identified as part of the methodology per se. The point may be made, however, that while consideration of the education of users is an extremely important part of any decision-making process, the behaviour of drivers occurs within the context of an entire tunnel system. The behaviour of drivers is affected by infrastructure and operation, not 'education' alone. The need to consider the education of users should not be used as a reason for failing to give due weight to other aspects of the system such as infrastructure, vehicle construction, condition and loads; as well as operation. (see Section 2 and Section 7, Road Tunnels, point (a)).

Commissioning Tests

Also, it is important for commissioning tests for new tunnels to be carried out in as realistic terms as possible. There has been a trend recently for tests of the ventilation system, for example, to be simulated using CFD, presumably in order to save money. This is not a good trend. CFD is a theoretical model, it is not the real world.

Measures need to be taken to try to ensure that commissioning tests are carried out in as realistic a way as possible. Conducting 'tests' through theoretical models alone is not adequate.

The 'FORUM' of Fire Research Directors

The international forum of fire research directors, known as the 'FORUM', has produced a "position paper" on "future actions for improving road tunnel safety", see [Ingason, H. & Wickstrom, U., 2006]. The 'FORUM' is a group of directors of institutions engaged in fire research.

Tunnel Fire Dynamics

Better understanding of tunnel fire dynamics is also essential; for example, the conditions for fire spread. New theoretical work and the creation of new theoretical tools to relate features of a tunnel system to consequences is essential. We need new probabilistic and stochastic models which are capable of being employed in a risk assessment. For the principle of 'equivalence' to have any effect this is vital.

Reporting and Analysis of Incidents

There needs to be comprehensive and uniform reporting of incidents across Europe. At present different countries have different criteria for reporting, different procedures and different reporting forms. There needs to be a uniform reporting system and it needs to be comprehensive.

As well as more serious incidents, it must pick up minor incidents, including those which have no ill effect associated with them but which are important in understanding how a more serious event might come about. This is very important, it helps understanding of the causes and dynamics of tunnel incidents and also is necessary in order to calculate probabilities more reliably. For example, the probability of a fire starting in a tunnel cannot be reliably calculated if many incidents are not known about. Incident reporting should also include information on human behaviour, both travellers and operators/emergency services. For example, real-world empirical information on, eg, whether or not drivers stay in their vehicles during an incident is very important. Information on the actions of operators and fire brigades would also be extremely valuable.

Further, the knowledge base needs to include in-depth studies of both (1) Serious incidents and (2) Minor incidents which may have become much more serious i.e. ‘near misses’.

‘Buried’ Research

In addition, ‘buried’ research results need to be brought to the fore and made readily available to those who need to know. ‘Buried’ research is that which has been reported in research publications and has a relevance (perhaps a strong relevance) to a particular risk assessment, but which the person conducting the risk assessment is unaware of, or is unaware of the relevance to their risk assessment. ‘Buried’ research results from 1971 may have helped to avoid the King’s Cross Underground Station disaster in London (1987) if they had been more prominently available and incorporated into a continual risk assessment, see [Beard, A.N., 2004].

A ‘One Stop Shop’

The establishment of a permanent ‘one stop shop’ at a European level, covering all aspects of the knowledge base and current research, from whatever source, would be a very desirable development. Such a ‘shop’ would act as a vital resource for all who wish to know, in order to conduct risk assessments on as sound and reliable a basis as possible.

EuroTAP

A points scheme approach (see Section 3.4.1 above) has been applied to existing tunnels in Europe, under the aegis of the German Automobile Association, ADAC. The most recent test is [EuroTAP, 2006] which gives a final ‘point’ for each tunnel corresponding to ‘very good’, ‘good’, ‘acceptable’, ‘poor’, ‘very poor’. In the 2006 ranking, 8 tunnels out of 52 were rated as ‘very poor’.

4 Regulatory Initiatives

Road Tunnels

The European Parliament and Council issued a Directive on “minimum requirements for tunnels in the Trans-European Road Network” in 2004; [EU Directive, 2004].

As an example, a comparison of ventilation requirements for Germany (D) and Switzerland (CH) with the new Directive has been given in [Dix, A., 2004] for the case of uni-directional congested tunnels of different lengths. Table 8 has been abstracted from that comparison for the case of mechanical ventilation requirements.

Perhaps the most notable point is that mechanical ventilation is required in shorter tunnels for both countries [op. cit], by comparison with the Directive. Dix makes the point that the Directive provides a minimal provision for safety but this may not be enough to discharge the legal responsibility of engineers.

The Directive says that it aims to provide a “minimum level of safety” and it seeks to do this by the prevention of crucial events (as described in Section 3.6 above), which it calls “critical events”.

Table 8: Comparison of requirements for mechanical ventilation in tunnels for EU Directive (EU); Germany (D) and Switzerland (CH). For the case of uni-directional congested tunnels of different lengths Re-drawn from [Dix, A., 2004a] Key:

Tunnel length (m)	*<100*	*100-500*	*500-600*	*600-800*	*800-1000*	*1000-1200*	*1200-1500*	*1500-3000*	*>3000*	*NB*
EU	♦	♦	♦	♦	♦	●	●	●	●	RA
D	♦	●	●	●	●	●	●	●	●	DD
CH	♦	♦	♦	♦	●	●	●	●	●	LR
CH	♦	♦	♦	●	●	●	●	●	●	HR

● Not mandatory for all tunnels;

♦ Mandatory for all tunnels

NB:

RA = May be varied if risk assessment demonstrates acceptable in special circumstances;

DD = Detailed decisions about smoke extraction etc driven by requirements of fire case;

LR = Lower risk-ventilation decisions driven by risk analysis;

HR = Higher risk-ventilation decisions driven by risk analysis.

The ‘Equivalence’ Principle

The Directive also invokes the concept of ‘equivalence’ in that the implementation of a specific measure may not be required if it can be shown that an alternative measure is ‘equivalent’ in terms of risk. This implies the use of models and risk analysis.

UPTUN & SAFE-T work on Risk Assessment

As part of the UPTUN initiative a document on tunnel risk assessment is due during the latter part of 2007; currently this appears to have been held up because of legal considerations. Also, as part of the SAFE-T initiative, work on 'Harmonized Risk Assessment' has taken place and an initial document was published in November 2004, [SAFE-T, 2004]. See also, [SAFE-T, 2006] mentioned in relation to 'PIARC Initiatives' above, Section 3.7 and [SAFE-T, 2007] on 'Guidelines for Tunnel Safety', which is aimed at improving safety in existing tunnels.

Rail Tunnels

UIC (Union Internationale des Chemins de Fer) is the umbrella organization of railways world-wide. A document on tunnel safety was published in August 2003 as UIC Codex779-9.

UNECE (United Nations Economic Commission for Europe) published a document on tunnel safety in December 2003, [UNECE, 2003].

ERA (European Railway Agency) has produced two preliminary documents pertinent to risk assessment; one on 'Common Safety Targets (CST)' and one on 'Common Safety Methods (CSM)' [ERA, 2006; ERA, 2006a]. The work is continuing.

The European Commission is pursuing 'Inter-operability' of the European railway system, aimed at trains from one country being able to operate in another country (see entry on the Channel Tunnel Rail Link and [Interop, 2006]).

5 Other Influences on Tunnel Safety

The Insurance Industry

The global re-insurance companies are beginning to require that risk management techniques be applied to tunnel construction projects. This initiative comes from major insurance companies such as Swiss Re and Allianz AG and a document has been prepared under the aegis of The International Tunnelling Insurance Group,

[ITIG, 2006]. This is expected to have a major impact on tunnel construction projects, [Dix, A., 2004b]. It may well have an effect on design and operation as well. This is because if the Code is not met during construction then insurers may withdraw cover and without insurance then projects will not be able to continue. The broad approach of the Code is the 'ALARP' approach described in Section 3.5 above.

Pension Funds and large Investors

It is important to note that large investors such as pension funds may have a significant effect on safety operation. It has been reported that 39 of the UK's public sector pension funds have told the oil company BP to improve its safety record or face a remunerations block. While not directly related to tunnel safety, it is an example of how a large investor can affect risk, [Daily Telegraph, 2007].

More generally, the point may be made that risk assessment techniques have been used in the oil industry for many years and yet this has not necessarily guaranteed an 'acceptable' level of risk in the eyes of all concerned.

Global Warming and Rising Sea Levels

Some tunnels may be vulnerable to rising sea levels [Dix, A., 2007]. Also, infrastructure equipment, such as electricity supply systems for tunnels, may be vulnerable to increased temperatures or flooding. The Netherlands has centuries of experience of coping with the threat of flooding; it would be desirable to learn from them in this context. Rising temperatures may also create direct health-related problems in some tunnels or metro systems; e.g. some passengers on London Underground have suffered ill effects from high temperatures in the past and passengers are advised to carry a bottle of water with them. A comprehensive assessment should be carried out to determine possible threats arising from global warming and to identify any vulnerable tunnels or metro systems.

Malicious Acts

The possibility of a malicious act resulting in an incident should be considered in any risk assessment.

6 Particular Tunnel Cases

As part of this project some particular tunnel cases have been considered in an attempt to ascertain what has happened, or is happening, with regard to tunnel design and risk assessment. As a general rule it has proven very difficult to find out how the decisions for a final design were reached. However, it is hoped that these will serve as examples and to some degree may illustrate the range of designs in existence today. To what extent some of these tunnels illustrate what may be regarded as 'best practice' is a matter of opinion. As has been pointed out earlier in this paper, what constitutes 'best practice' is certainly not a matter of universal agreement. These descriptions are not intended to be exhaustive. They are simply intended to give an indication of some of the features present in some specific tunnel designs. The particular cases considered are:

European tunnels

(1) The Channel Tunnel {Rail}, UK-France; (2) The Oresund Link {Road and Rail}, Denmark-Sweden; (3) The Bologna/Firenze high speed rail link, Italy; (4) The Channel Tunnel Rail Link (CTRL), UK; (5) The Gotthard Base Tunnel (Rail), Switzerland, (6) The Great Belt Rail Link, Denmark.

Non-European tunnels

(7) The Burnley Tunnel {Road}, Melbourne, Australia; (8) The Trans Tokyo Bay Tunnel {Road}, Japan; (9) The West Rail Tai Lam Tunnel, Hong Kong; (10) The Shuesan Tunnel {Road}, Taiwan and (11) The Ted Williams Tunnel {Road}, Boston, USA.

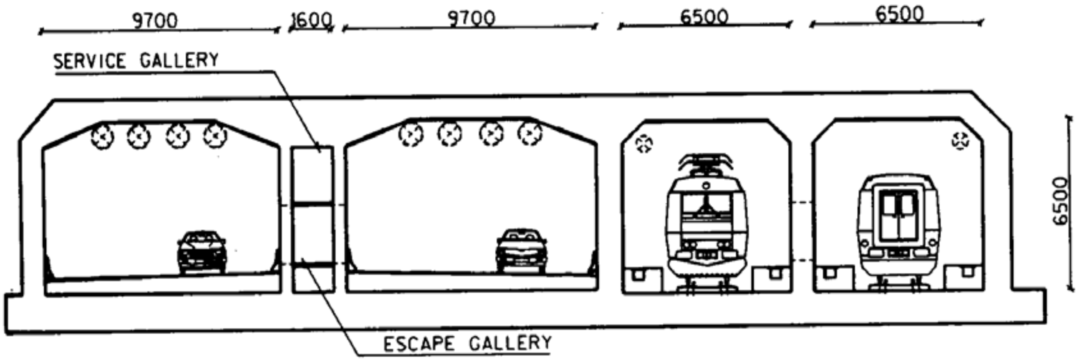
European Tunnels

(1) The Channel Tunnel. This consists of a bored tunnel system, approximately 50 km in length; it was completed in 1994. The system consists of three parallel tunnels: two uni-directional railway tunnels and a third tunnel, between the two, to act as a service and safety tunnel. Cross-passages connect the 'running' tunnels to the service tunnel. The criteria for acceptability of risk have been referred to briefly in Section 3.5 above.

(2) The Oresund Link.

This is a link between Copenhagen in Denmark and Malmo in Sweden. It is approximately 16 km long and includes a bridge and an immersed tunnel of approximately 4 km length. It was completed in 2000. The tunnel system carries both road and rail traffic. It consists of two uni-directional rail tunnels and two uni-directional road tunnels. All four tunnels are parallel. Between the two road tunnels there is a very narrow tunnel, or 'central gallery', which runs the length of the tunnels. The central gallery consists of three smaller 'galleries', one on top of the other: at the top is a 'service gallery', below that is an 'escape gallery' and below that is a small gallery for fire mains and drainage pipes; see Figure 14. There are cross-passages between the road tunnels and the narrow tunnel. The criteria for acceptability of risk have been described briefly in Section 3.5 above. (There is a section with five articles on the Link in [SIRRT, 1998].

Figure 14: The Oresund Link: cross-section of the Drogden Tunnel
(Distances shown in millimetres)



(3) The Bologna/Firenze High Speed Rail Link.

The entire link is 78 km long of which approximately 73 km consists of tunnels, including 9 major tunnels. The tunnels have been described as “difficult”, [Tunnel Machines, 1999]. The longest is the Vaglia Tunnel, 18.6 km long, then the Firenzuola Tunnel, 15.3 km long, followed by the Pianoro tunnel at 10.7 km long. These tunnels are single bore, double-track tunnels. At present the project appears to be about 82% complete. Difficulties have been encountered, such as the fracturing of an aquifer [Piccinini, L.; Vincenzi, V., 2005]. There are, further, litigation cases [TAV, 2002, 2004]. TAV also reports on an attempt to prevent the involvement of criminal organizations, although it is not clear to what extent this may involve the Bologna-Firenze line. It has proved difficult to ascertain what has been done with regard to the risk assessment for these tunnels and details of the design; a large number of different companies are involved. The decision-making for the designs of the tunnels appears to have included risk assessment, in particular, probabilistic methods, [Focaracci, A., 2007; Focaracci, A, 2007a]. For societal risk a F-N curve approach seems to have been adopted, assuming an ALARP principle (see Section 3.5). In the Firenzuola Tunnel the distances between emergency exits/portals are given as: 1.6 km, 1.7 km, 3.3 km, 3.45 km, 5.0 km. There are also “galleries” accessible to vehicles. For the Vaglia Tunnel the distances between emergency exits/portals are given as: 4.5 km, 4.3 km, 1.95 km. There is also a 8 km section with a service tube, having cross-links to the operational tube every 250 m (see [AlpTransit, 2003]). There appears to be no longitudinal ventilation in the operational tubes of the Firenzuola or Vaglia Tunnels; it is unclear whether or not there is a different form of ventilation (i.e. non-longitudinal). There is a “smoke filter” in emergency exits, [op.cit.].

(4) The Channel Tunnel High Speed Rail Link.

This Link will join London and the Channel Tunnel near Folkestone. It is due to open in November 2007 and will be about 108 km long of which approximately 27 km will be in tunnels. The main section consists of a ‘London Tunnels’ part approximately 17.5 km in length. This consists of two sections with an underground station at Stratford connecting the two. The two sections consist of a tunnel approximately 7.5 km long from King’s Cross to the west end of the ‘Stratford Box’ (which is approximately 1 kmlong); and a second tunnel, approximately 10 km long, from the east end of the ‘Box’ to the ‘Ripple Lane Portal’. After that there is a ‘Thames Tunnel’, approximately 3.1 km long, taking the CTRL under the River Thames. Beyond the ‘Thames Tunnel’ the longest tunnel is the North Downs Tunnel in Kent at about 3.2 km long.

The London Tunnels and the Thames Tunnel are twin bore, uni-directional tunnels. The North Downs Tunnel is a single bore, double track tunnel. For environmental reasons (the area above, Bluebell hill, is regarded as being of 'outstanding natural beauty') no pressure relief shafts were allowed to vent into the atmosphere above. In order to allow for this the cross-section of the tunnel has been made larger than normal, at 174 m^2, and is the largest cross-section of any rail tunnel in Europe.

There are five ventilation shafts along the London Tunnels and Emergency Response Locations (ERLs) are placed at each of the ventilation shafts. Each shaft is fitted with: access stairs, fire hardened lift, pressurized fire-fighters' lobby. Cross-passages are positioned at the base of each ventilation shaft with two further cross-passages positioned at approximately 70m and 445m from the ventilation shafts. Intermediate cross-passages between the ERLs are at 750m spacings although in practice some distances exceed 750m. The average spacing of non-ERL cross-passages is 663m; [CTRL, 2007]. It was decided that an "original 375m cross-passage scheme was not reasonably practicable because the cost was grossly disproportionate to the safety benefit gained, even if the statistical value for each casualty avoided was taken to be £4m", [Scott, P., 1998].

The 'Thames Tunnel' has five cross-passages at spacings of 670m. The decision on this was reached via a cost-benefit analysis in which a value of a life of £2m was used where the overall number of fatalities is less than 100 and £4m where the overall number of fatalities is greater than 100, [CTRL, 2000]. A 'Train Accident Risk Model' was devised, based on fault tree and event tree probabilistic concepts and incorporated into a spread-sheet model, [Small, L., 2004].

If an incident occurs on a train, such as a fire, "CTRL procedures require that the train stops before the tunnel or proceeds out of the tunnel, if it is safe to do so", [CTRL, 2007]. If it is not possible to proceed out of the tunnel then " a driver will stop at an ERL….if not an ERL, then a point at which an intermediate cross-passage door is level with the first train carriage door..", [op.cit.].

The comment may be made: how would a driver know that it would not be possible to drive to an ERL? During the Channel Tunnel fire of 1996 the train which was on fire lost power and the policy of driving out was not possible. If this were to happen in a CTRL tunnel it may not be possible to drive to an ERL, but the driver may not realize this, and the option of a controlled stop by a cross-passage door may be lost. Perhaps this possibility has been accounted for in the design of the CTRL, although it is not apparent to the author of this report from the material which has been gathered.

It was decided not to have fire detectors in the CTRL tunnels based on the argument that there is a "known unreliability of fire detection equipment in the Channel Tunnel and other tunnels", [CTRL, 2007]. Note also that in relation to the Ted Williams Tunnel, Boston, the heat detectors were found to be slow in reacting; see entry later in this Section.

The basic approach in the safety decision-making was to use the 'As Low As Reasonably Practicable (ALARP)' approach; see Section 3.5 above.

The safety management system was based on the guidelines set out by the UK Health and Safety Executive, [HSG65, 1997]. The most recent regulatory change to affect the project was the introduction of the 'Railways (Inter-operability)(High Speed) Regulations', which came into effect in the UK in 2002, [Interop, 2002]. The inter-operability regulations apply throughout the European Union and define requirements (one of which relates to safety) for sub-systems which make up a railway.

A sub-system which has been approved under these regulations in one member state can be introduced into another without further approval, [Small, L., 2004].

(5) The Gotthard Base Tunnel (rail), Switzerland.

This tunnel is currently under construction and is due for completion in 2012. At 57 km it will be the longest tunnel in the world and will carry a high speed railway line with passenger trains expected to run at 250 km/hr, [Kauer, C., 2001]. There are likely to be more than 300 trains per day, including freight trains; it will be allowed to admit trains carrying "hazardous goods". It is expected that it will become a major feature of the connection between Zurich and Milan and, beyond that, between Germany and Italy in general.

The tunnel will consist of two uni-directional tubes with cross passages approximately every 325 m [op.cit.] to allow evacuation from one tube to another. The "self rescue" concept has been adopted, [Gerber, P, 2001]. It has been estimated that in "almost every incident an evacuation train or the fire fighting and rescue train" will arrive "on the spot within 35 to 45 minutes approximately; the evacuation of the passengers will be completed after 90 minutes at the latest". A feature of the design is the inclusion of two "emergency stop stations" in the tunnel [op.cit.]. It is intended, in case of emergency, that a passenger train should be able to reach an emergency stop station (or, presumably, the exit of the tunnel). For information on the criteria for acceptability of risk for this tunnel see Section 3.5.

(6) The Great Belt Rail Link, Denmark.

This Link runs between Nyborg on the island of Funen and Korsor on the island of Zealand. It consists of a bridge which is 8 km long, the island of Sprogo which is 2 km long and a tunnel which is 8 km long. The tunnel consists of two tubes with cross-passages at intervals of 250 m. It went into operation in 1997. The evacuation procedure assumes a 'self rescue' philosophy, [Rasmussen, A., 2001]. Thus far "there have been no train accidents with subsequent action by rescue services", [op.cit.].

Non-European Tunnels

(7) The Burnley Tunnel (road), Melbourne, Australia.

The Burnley Tunnel is approximately 3.4 km long and carries traffic under the Yarra River; it was opened in 2001. It consists of two uni-directional tubes, each with three lanes and cross-passages between the tubes. For fire suppression purposes it has a deluge water system and also has a dedicated smoke extraction system. There is a CCTV system to enable the control room staff to monitor events in the tunnel. It has a semi-transverse ventilation system as well as a longitudinal ventilation system.

There was a fire in this tunnel in March 2007 in which the deluge system was activated. (see also, Section 2).

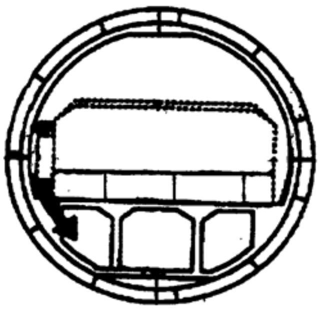
(8) The Trans Tokyo Bay (road) Tunnel, Japan.

This tunnel is part of a 15 km link across Tokyo Bay. The link consists of a 9.5 km long tunnel and a 4.4 km long bridge, together with two man-made islands. In broad concept it bears some similarities to the Oresund link between Denmark and Sweden although the Trans Tokyo Bay (TTB) link is for road traffic only. It was opened in December 1997. The tunnel is the longest under-water road tunnel in Japan and consists of two uni-directional tubes, each tube having two lanes.

Vehicles carrying so-called ‘dangerous goods’ (i.e. chemicals/petrol etc) are not allowed in the tunnel; in Japan ‘dangerous goods’ vehicles are not allowed in under-water tunnels or tunnels longer than 5 km, [Iwate, H.; Ota, Y., 2001]. The tunnel has a water sprinkler system with a foam option. The ventilation system is longitudinal and the tubes also have electro-static precipitators, [Yamada, N.; Ota, Y., 1999]. (Electrostatic precipitators have the capacity to remove some of the solid particles, primarily soot, from the air)

It was originally intended to have cross-passages between the two tubes at approximately 750m spacings. However, if an earthquake were to occur the two tubes would be expected to move separately, creating large stresses on any cross-passage connection. For this reason it was decided to use the space below the roadway as an evacuation space, with slides connecting the upper and lower levels; space to install staircases was considered not to be available [op. cit.]. The slide arrangement is indicated schematically in Figure 15.

Figure 15: Trans Tokyo Bay Tunnel: cross-section of one tube of a twin-tube tunnel; illustrating the general principle of a slide (arrow) from the road-way level to an evacuation space below.



Because the capacity of each slide is less than that of a cross-passage, slides have been installed at intervals of approximately 300m.

(9) The West Rail Tail Lam Tunnel, Hong Kong.

The ‘West Rail’ runs between West Kowloon and Tuen Mun in the New Territories; the tunnel passes under the Tai Lam Country Park. It was completed in 2003 and is operated by the Kowloon-Canton Railway Corporation. The tunnel consists of a single tube and is about 5.5 km long. It contains two tracks, separated by a dividing wall, with trains running in opposite directions. There are cross-passages at 60m intervals in the dividing wall to enable evacuation from one side to the other in case of emergency. Functionally it is effectively two tunnels with connections. A cross-over facility is provided at about the mid-way point, with an opening of about 54m in the partition wall; during normal operation the cross-over opening would be closed. There was a fire in the tunnel in February, 2007; see Section 2 and [Plumbridge, G., 2006], [Maunsell, undated].

(10) The Shuesan (road) Tunnel, Taiwan.

This tunnel was opened in 2006 and is 12.9 km long, [Lin, C.; Ota, Y., 2005]. It forms part of the east coast highway being constructed between Iran City, close to Taipei, and Hualien City further south. The tunnel consists of two uni-directional tubes with cross passages every 350m between the tubes for escape. It also contains ‘U-turn structures’ for maintenance and emergency vehicles at intervals of approximately 1to1.3 km through the tunnel. There are also CCTV cameras and carbon monoxide monitors.

The tubes have longitudinal ventilation systems, with smoke extraction points (having dampers) located along the ceilings. In the event of a fire, the damper closest to the fire on the downstream side (i.e. direction of traffic flow) should open and smoke be extracted using the longitudinal ventilation to push smoke towards the open damper from both sides. Smoke would then be expelled through vertical shafts.

(11) The Ted Williams (road) Tunnel, Boston, USA.

As a general rule, with regard to fire safety, road tunnels in the USA are designed on the basis of a document published by the National Fire Protection Association (NFPA), see [NFPA, 2004]; this has been updated and a new version is set for 2008. This tends to set requirements for sub-systems such as “Motorists should not be exposed to maximum air temperatures that exceed 60oC (140oF) during emergencies”, see [NFPA, 2004; Annex B]. The Ted Williams tunnel is approximately 2.6 km long and is part of the extensive ‘Central Artery Project’, which includes roadways and three tunnels, in Boston, [Comeau, E.; Flynn, W., 2003]. The tunnel is bi-directional and eight lanes wide (four lanes each way); it was opened in 1995. There are CCTV cameras and carbon monoxide (CO) monitors. The CO monitors are there primarily for air quality control, but also function as an indicator if there is a fire. There is a linear fire detection system. However, during a fire in the tunnel in 2002 a bus ignited and stopped, [Beard, A. N.; Carvel, R. O., 2005]. The first alarm to the control centre came from the CO detectors; the linear heat detectors did not operate until after the fire brigade was on the scene.

The ventilation system is fully transverse and in the case of a fire may be used to extract smoke, [Levy, S. S.; Sandzimier, J. R., 2000]. The ventilation, fire detection and traffic control systems are run through a system known as the Integrated Project Control System (IPCS), run from the control room in South Boston. The IPCS is stated as being “redundant”, with a back-up system in another building less than a quarter of a mile away. For evacuation, there are a series of emergency doors located approximately every 305 m which lead people either to the surface via stairs or to an adjacent tunnel via a cross-passage. Motion sensors have been installed outside ventilation buildings and at other high-security locations; this was spurred by the attack on the World Trade Towers in New York on September 11th 2001.

7 Some Strategic and Specific Issues

Some Strategic Issues

In a move towards employing risk assessment as part of decision-making on safety:

(1) Fatality or injury is a systemic product. Harm results from the working of an entire system. This involves: infrastructure, operation, vehicles, vehicle contents, people; as well as socio-economic and political factors. Regulation, as well as tunnel design and operation, needs to reflect this.

(2) The ‘system’ leading to fatality or injury is continually changing. How do we create a risk assessment structure which is capable of coping with this?

(3) Safety considerations need to be in at the very beginning of a design process for a new tunnel; or a process to consider operation for an existing tunnel.

(4) What is a ‘healthy mixture’ of prescriptive requirements, qualitative risk assessment and quantitative risk assessment? Some countries, most notably Japan, do not use risk assessment (i.e. quantitative risk assessment at least) other than, possibly, in extremely rare cases; the authors are not aware of any specific case in which risk assessment methods have been used. (The Trans Tokyo Bay Tunnel has been described as “slightly different from other tunnels”, [Ota, Y., 2007]). The essence of the system for road tunnels seems to be to assign a new or existing tunnel to one of five categories based on tunnel length and traffic volume. Measures to be employed largely derive from that categorization, see [Ota, Y., 2003]. It may be noted that water sprinkler systems have been installed in road tunnels in Japan since the latter half of the 1960s; a summary of the Japanese approach to road tunnel safety is contained in [Mashimo, H., 2002]. It would be wise to look in detail at what has been done and what is currently done with regard to tunnel safety in Japan in attempting to decide what is a healthy mixture of prescriptive requirements and risk assessment.

(5) To what extent does the process of risk assessment and decision-making methodology need to be the same across different countries?

(6) Methodology for Design including Risk Assessment. A methodology (or criteria for such) for design including risk assessment needs to be created. Such a methodology would be exhaustive and comprehensive. A methodology such as that indicated in Section 3.3 above may be regarded as generic enough to allow for different approaches within it.

(7) What are to be the criteria for acceptability of risk?

(8) Criteria for acceptability: should road risk be higher than for rail?

(9) Should the European Union adopt a ‘Vision Zero’ policy?

(10) How might a regulatory framework which will ensure, as far as possible, the acceptable use of models as part of tunnel safety decision making be established? What would such a framework consist of?

(11) Computer source codes for models which are used as part of safety decision-making should be open to scrutiny by the public in general and the scientific community in particular. Large sums of money should not be demanded to obtain a source code. Codes should be freely available or available at a nominal charge to cover the immediate costs of production of a copy of the code and postage.

(12) The knowledge base and research. We know much more about the tunnel system in relation to safety than we did twenty years ago. However, much remains to be done. Both theoretical and experimental work is necessary. Adequate theoretical techniques need to be created in order to be able to support a risk assessment (e.g. at present we do not have sufficient models, probabilistic or deterministic, which relate features of the system to predicted variables e.g. heat release rate or fatalities/injuries). In experimental work it is, in particular, very important to have large-scale tests as well as small-scale ones. Experimental testing cannot be replaced by computer-based simulations. Also, it is necessary to know much more about human behaviour. Operation needs to be studied in detail and different options examined. Devising an efficacious, systemic, safety management system is a main concern. As 'the system changes' research needs to be on a continual basis.

(13) The knowledge/practice interface and a 'One Stop Shop'. The interface between sources of knowledge and those who wish to know needs to be improved considerably. 'Sources of knowledge' here is intended to be exhaustive and comprehensive; it would include research and other sources of knowledge such as incident statistics. Further, it should gather information globally, not just from European sources; and make spontaneous efforts to inform those who should know. It would be desirable for a formal, permanent, body to be established to carry out this function. Such a body might be called, eg, the 'Office for the Knowledge/Practice Interface' or similar. As part of this one might envisage a 'One Stop Shop' between sources of knowledge and those who wish to know. Such a 'shop' would readily supply information upon request. It would also include information on what research is being conducted and how. This links to point [14] below. An 'interface body' of this kind would have relevance to the built environment in general, not just tunnel safety.

(14) In order to support modelling activities there is a need for an information base consisting of empirical results and statistical data. As 'the system changes' continually this would need to be up-dated on a continual basis. At the present time, for example, it does not seem to be the case that statistical data, and information in general, on incidents in tunnels is collected centrally in the European Union or world-wide. This also links to [15] below.

(15) Reporting of Incidents. The reporting of incidents needs to be carried out on a uniform and consistent basis across the European Union, using a single reporting form; or, at least, consistent reporting forms. Reporting should be exhaustive and comprehensive, including minor incidents as well as serious ones.

(16) It would be desirable to create a tunnel safety 'Management Unit' at a Europe-wide level; especially a Europe-wide 'System 4' (see 'Safety Management System', Section 3.6 above).

(17) How is 'engineering judgement', and 'expert judgement' in general, to be incorporated into a risk assessment?

(18) 'Best practice'. Opinions differ as to what constitutes 'best practice'. Also, what may be regarded as 'best practice' changes with time. If the concept of 'best practice' is to be employed then a mechanism needs to be established to decide what it would consist of. Such a mechanism would need to be in continual existence to allow for changes over time. Once a 'best practice' procedure has been decided upon then it should not be possible to avoid it on grounds of cost.

(19) Malicious Acts. The possible effect of malicious acts on tunnel safety risk assessment should be considered.

Some Specific Issues

Generic:

a) Incident response. To what extent should incident response by the operator be ‘automated’ and made simple? How can this be made to dove-tail with the emergency services?

b) Safety management system. What kind of safety management system should be in place?

c) Malicious acts. It needs to be decided whether measures adopted for non-malicious acts are adequate for incidents resulting from malicious acts. This may be of particular importance for underground railway/metro systems. In this context it may be noted that fire extinguishers have been removed from railway carriages on the London Underground system. Whatever the reason for removal of the extinguishers, the risk if a fire were to start in a carriage is evidently greater than otherwise, whether a fire were to be malicious or not.

d) Global warming and rising sea levels: what might be the effects on tunnel safety?

e) Inherently Safer Design (ISD). The concept of inherently safer design (ISD) has been used in other fields, e.g. the chemical industry. How such concepts might be applied in the case of tunnels needs to be investigated. ISD implies taking specific measures which, in themselves, imply a safer outcome to any incident. In the chemical industry, for example, it implies ensuring the inventory (stock of flammable materials) is as low as possible. Other ISD measures might include using intrinsically safe electrical equipment (i.e. with spark energy below that necessary to cause an explosion) or operating procedures which eliminate the chance of explosion by avoiding chemical ‘flammability regions’.

   What might be equivalents in the tunnel context should be investigated in detail. No doubt some ISD measures are employed already; whether consciously or unconciously as ISD. Tunnel related ISD measures might include using fire-retarded or fire-resistant materials as far as possible (although some fire-retarded materials produce more smoke than non-fire-retarded.) It might also include ensuring that the most suitable track is in place for a given train type, to try to reduce the chance of de-railment [Favre, P., 2001]. (In this regard, for example, it may be mentioned that the track in the Channel Tunnel appears to be a compromise between that optimal for passenger traffic and that optimal for freight traffic; this would need to be verified. This may be the case for other lines as well.) See also (f) below.

f) Contents of vehicles or railway carriages.

   Principal factors creating risk in tunnels may generally be regarded as: infrastructure, vehicles/rolling stock (including traffic patterns), operation and people’s behaviour. However, it has become evident that another very important factor is the *contents* of the vehicles or railway carriages. In the Kaprun railway disaster of 2000, [Schupfer, H, 2001], [Beard. A. N.; Carvel R. O., 2005], the rolling stock had been regarded as ‘fire-proof’. However, a prime factor in the spread of the fire, leading to many deaths, appears to have been the contents of the carriages; i.e. the clothing of the passengers and the items they were carrying. It is difficult to control contents of road vehicles or railway carriages; however it certainly needs to be included in any risk assessment. Ways to control contents need to be devised. Regulations on the production of the goods at source (clothing and carried items, luggage etc) should be introduced. See also (e) above.

g) Human behaviour. Awareness of real human behaviour, as opposed to idealized expectations, needs to be incorporated into design and operation. This applies to the behaviour of tunnel users, operational staff and emergency services.

h) Design for Evacuation and Rescue; especially of the Elderly and Disabled.

   There is considerable variation within the population with regard to characteristics and capacities. In particular, the capacities of the elderly and disabled are generally very different to those of an 'average' person. Approximately 20% of the population of the European Union is over 60 years old and about 9% of the population of the EU is disabled [Sire, E. et al., 2003]. This corresponds to many millions of people. Research is needed to ascertain the behaviour of the elderly and disabled as well as the 'average' person.

   At the present time, in general, we seem to be designing our systems for the 'average' person. If we wish to design for the evacuation or rescue of elderly and disabled people then adequate provision must be made for this. For example, the [OPECST, 2000] report makes the point that, for sufficiently long bi-tunnels there should be a capacity for motorized transport along a sufficiently large evacuation gallery, to allow for people with reduced mobility.

   (For uni-directional tunnels, escape could be through a parallel tunnel, in most cases with transport for evacuation through the second tunnel.) In addition, it may be argued that the system should be able to get people to and through an escape door, leading from the fire tunnel itself. A philosophy of 'self rescue', which is common, may not be suitable.

   The European Parliament needs to decide what is to be regarded as acceptable; i.e. whether evacuation systems are to be based on the 'average' person only or whether our designs are to take explicit account of the variability within the population and, in particular, the needs of elderly and disabled people; with an aim of achieving evacuation without harm.

i) Robustness. In any complex system there will almost certainly be unintended consequences resulting from any decision. Because of this, tunnel safety decision making and regulation needs to be sufficiently robust as to allow for the unanticipated. Designing 'too close to the wire' by having too much faith in our methods and numbers is unwise. There needs to be sufficient 'slack' in design and operation so as to allow for the unanticipated. In short, our designs and operational procedures need to be robust.

j) Fire suppression. Historically, the great majority of tunnels in Europe have not incorporated fire suppression. This needs to be seriously considered in relation to future regulation. In other countries, most notably Japan and Australia, fire suppression systems are installed much more often than in Europe.

k) Smoke control. In general, ventilation systems which extract smoke are preferable to ones which simply push smoke from one place to another within a tunnel. The suitability of systems which only do the latter needs to be addressed as part of an entire consideration of regulation with respect to smoke control.

l) Ventilation system. The ventilation system may seriously affect a fire and increase the chance of spread dramatically. This needs to be effectively addressed.

m) Protection of tunnel structure. Might the inclusion of protective linings actually make a fire worse and result in more fatalities than otherwise; because of heat retention in the tunnel itself? This needs to be considered in any risk assessment.

n) Insulation to conserve energy. Might the use of insulation for energy conservation purposes actually increase the severity of a fire, because of heat retention? This is a similar point to that above and would need to be considered in any risk assessment.

o) Terminology: it would be desirable for uniformity in the use of terminology to be encouraged. The publication of *The Handbook of Tunnel Fire Safety* [Beard, A. N.; Carvel, R. O., 2005] may be regarded as a first step in attempting to establish a common terminology.

Road tunnels:

a) Non-fire incidents.

Most fatalities in tunnels result from accidents which do not involve fire. A concerted effort needs to be made to address this; particularly through measures aimed at avoiding collisions. This may involve measures affecting infrastructure or operation as well as educational measures aimed at affecting the behaviour of drivers. It becomes necessary to know the psychologies of different kinds of drivers; e.g. regular users or non-regular users. The condition of each vehicle is also an important factor. It is necessary for a tunnel operator to become very familiar with the kinds of drivers and vehicles/loads passing through the tunnel. Measures aimed at reducing the incidence of common traffic accidents would also be expected to reduce the probability of a fire-related incident (see also, Section 2 and point (g) above).

b) HGVs.

It is evident that fires involving HGVs present a major problem. Effective control needs to be brought about through a combination of prevention and protection. To a lesser extent this is also true of lighter goods vehicles, coaches and buses. The matter of 'dangerous goods' is being addressed and it is appropriate that it be so. However, common-place goods, such as furniture, also have the potential to produce catastrophic fires in tunnels and these must also be regarded as 'dangerous'. This issue needs to be addressed in earnest. (This concern about HGVs also applies to the Channel Tunnel, which is a rail tunnel.).

c) Changes in traffic patterns, for example, the tendency for more goods to be transported by road.

d) Changes in vehicle construction and fuels used; for example, larger fuel tanks in HGVs and hydrogen-powered vehicles. How might these affect tunnel safety?

Rail tunnels:

a) Historically, on the whole, rail tunnels have had a better safety record than road tunnels. However, this should not induce us into a state of complacency. In [OPECST, 2000] it is pointed out that before the Mont Blanc fire of 1999 the tunnel had been regarded as relatively safe because in 34 years of operation only 17 fires had been reported, 12 of which had been extinguished by the drivers and 5 by the operators. If a study, based on historical statistics for the twenty years up to 1998, had been carried out for road tunnels then it would probably have led to the conclusion that there was not a lot to worry about concerning road tunnel safety, as far as deaths in Europe were concerned. See Table 9. However, we can see from Figure 3 that in the twenty years starting from 1987 there were approximately 96 deaths from fires in road tunnels, the great majority of which were in Europe.

b) There is a very large number of older tunnels, particularly in Europe, many of which are over a hundred years old. The average age for railway tunnels in Europe is 70 years, [Zuber, P., 2004]. Upgrading such tunnels to a much more acceptable standard presents a daunting prospect. Also access for a fire brigade to attempt to fight fires or mount rescue attempts in such tunnels is very problematic. For example, in the Mornay Tunnel fire (2003), there wasn't even a local water supply for the Fire Brigade to use [Carvel, R. O.; Marlair, G., 2005].

c) High-speed rail links present a new challenge; these need to be considered to try to understand what new hazards may be introduced and how harm may result from the system as a whole. For example, there may be an increased chance of de-railment or increased stress on rails. Also there may be increased noise and aerodynamic loading with the possibility of breakage of windows or doors. High-speed trains have been run in Japan since 1965 and it would be wise to look in detail at their knowledge and experience.

Table 9: Significant Road Tunnel Fires, 1979-1998. Not including 'under construction' or malicious; derived from information in [Carvel, R.; Marlair, G., 2005]

Number of fires	*Number of fatal fires*	*Total number of fatalities*
31 (inc. 25 in Europe)	12 (inc. 6 in Europe)	223 (inc. 26 in Europe)

8 Recommendations

Recommendations Affecting the Built Environment in General (i.e. both Tunnels and Non-Tunnels):

(1) An 'Office for the Knowledge/Practice Interface', or similar, be established at a European level and be maintained on a permanent basis (see Section 7, point [13]). A 'tunnel section' which collected statistical and other information and made it available would be a part of this (see Section 7, point [14]).

(2) A 'One Stop Shop' be established at a European level, as part of an 'Office for the Knowledge/Practice Interface' or similar (see recommendation 1 above and Section 7, point [13] and Section 3.7).

(3) An organization to carry out the function of a Europe-wide 'System 4' be established; i.e. an 'outside and future' system. (See Section 3.6). Such an organization would have a strong connection with an 'Office for the Knowledge/Practice Interface' and 'One Stop Shop', as mentioned in recommendations 1 and 2 above. Such a 'System 4' would have a 'tunnel section' to deal with tunnel safety.

(4) Source codes for computer-based models employed as part of safety decision-making be open and readily available, without conditions, to the public in general and the scientific community in particular. The producers of such codes shall not be able to demand money for supplying a code, other than a small amount corresponding to the *genuine and minimal* costs of copying and postage. (see Section 3.4.2)

(5) A regulatory framework be created in order for models, especially computer-based models, to become generally acceptable as part of safety decision-making. (see Section 3.4.2). This implies the following recommendations, *which should be seen as a whole*:

5.1 An independent Models Assessment Group (MAG) be established at a European level. The MAG would have subsidiary groups to consider different types of models and different applications e.g. tunnels/non-tunnels (see Section 3.4.2)

5.2 A Registration Council be established at a European level; in order to, after due consideration:

5.2.1 accept (or 'register') specific models for use in particular applications by 'registered' users employing an acceptable methodology of use;

5.2.2 accept (or 'register') particular 'methodologies of use' as acceptable for use in applying specific models for particular uses by 'registered' users (see Section 3.4.2);

5.2.3 accept (or 'register') particular users to employ an acceptable 'methodology of use' in applying a specific model to particular cases (see Section 3.4.2).

None of the above three sub-recommendations should be implemented in isolation; this would be expected to be counter-efficacious.

(6) Risk assessments employing models, especially computer-based models, be carried out by a person who is as independent as possible of the system or design under scrutiny, whether tunnel or non-tunnel. Such a person should be appointed by an independent regulatory body such as a building control office or fire brigade. A risk assessment should be checked by a second independent person.

Recommendations Affecting both Road and Rail Tunnels:

(7) Criteria for Acceptability of Risk be explicitly decided (see Section 3.5).

(8) Measures be taken to establish what is a 'healthy mixture' of prescriptive requirements, qualitative risk assessment and quantitative risk assessment in decision-making on safety. As part of these considerations it is recommended that the system and experience in Japan be examined (see Section 3 and Section 7, point [4]); and the system and experience in Australia be examined (see Section 2 and Section 6).

(9) Measures be taken to reverse the trend for an increasing proportion of goods to be transported by road rather than rail (see Section 2).

(10) A uniform system for reporting of incidents be created and adopted across Europe.

This would include minor incidents as well as major. It would also include 'near misses', i.e. incidents which very nearly could have been serious but in fact were not (see Section 3.7 and Section 7, point [15]).

(11) Measures be taken to improve the knowledge base. As 'the system changes' this needs to be on a continual basis. This would link to recommendation 3 above (see Section 3.7 and Section 7, point [12]).

(12) A body be established to determine what is to be accepted as 'Best Practice' in Europe (see Section 1.3 and Section 7, point [18]).

(13) Measures be taken to try to ensure that commissioning tests are carried out in as realistic a way as possible. Conducting 'tests' through the use of theoretical models alone is not adequate (see Section 3.7)

(14) A 'Tunnel Safety Management Unit' be created at a European level. This would link to recommendation 3 above (see Section 7, point [16]).

(15) Steps be taken to determine whether measures adopted for non-malicious acts are adequate for malicious acts; especially for underground railway/metro systems (see Section 7, point (c)). This links to recommendation 3.

(16) Steps be taken to determine what the principles of Inherently Safer Design (ISD) might imply for tunnels and appropriate measures be applied as far as possible. This would include considerations about contents of vehicles and railway carriages (see Section 7, Generic, points (e) and (f)).

(17) Steps be taken to determine what might be the effects of global warming and rising sea levels on tunnel safety (see Section 5). This links to recommendation 3.

(18) Steps be taken to ensure that designs for tunnel safety include acceptable measures for the evacuation of elderly and disabled people and not the 'average person' only (see Section 7, point (h)).

Road Tunnel Specific Recommendations:

(19) The Norwegian 'Vision Zero' policy, or similar, be adopted Europe-wide (see Section 3.5).

(20) Measures be taken to reduce deaths and injuries from common traffic (i.e. non- fire) accidents in road tunnels. (See Section 2 and Section 7, Road tunnels, point (a)).

(21) Measures be taken to address the very serious problem posed by heavy goods vehicles (HGVs) passing through tunnels (see Section 2 and Section 7, Road tunnels, point (b)). This links to recommendations 3 and 9.

(22) Measures be taken to try to ensure that the HGV fuel price is the same across Europe to reduce the trend to build HGVs with larger tank (see Section 2).

(23) Measures be taken to prevent hydrogen-powered vehicles passing through tunnels. This position to be maintained until a comprehensive and exhaustive independent assessment has been conducted. It seems very likely that, even after such an assessment, it would not be wise to allow hydrogen-powered vehicles into tunnels (see Section 3.6 and Section 7, Road tunnels, point (d)).

Rail Tunnel Specific Recommendations:

(24) Steps be taken to assess the stock of existing rail tunnels in Europe with respect to safety risk (see Section 2 and Section 7, Rail tunnels, points (a) and (b)).

(25) Steps be taken to assess new hazards posed by high-speed rail lines. As a part of this it is recommended that the situation in Japan be examined (see Section 7, Rail tunnels, point (c)).

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