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LIMITATIONS OF RISK ASSESSMENT METHODOLOGIES FOR FIRE IN TRANSPORT TUNNEL SYSTEMS

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ABSTRACT

This paper outlines how traditional risk methods can be improved by a new methodology for measuring risk based on the inherent risk potential of a system. The new method has the capacity to incorporate engineering and human factors and calculates the synergy of outcomes when the design is moved into the operational phase within the real risk environment. It is the hypothesis of this paper that traditional risk measurement approaches, while laudable and useful, cannot achieve the design goal of protecting life because the traditional conceptual understanding of risk is flawed by a failure to interpret the almost infinite sets of risk factors that will impact on the design over the life-time of the system. This is highlighted by analysis of fire in a transport tunnel which used worlds best practice for design but can still give rise to catastrophic outcomes from foreseeable events. The new risk methodology postulates a set of seven steps in a risk management approach that assesses the capacity of controls to protect the critical functions of the system – the most critical being that of protection of any person from death or irrecoverable injury – and provides for the introduction of new controls to manage foreseeable loss events.

Keywords: Risk Assessment, risk management, tunnel fires, rail transport.

INTRODUCTION

A new method for measuring the risk of catastrophic events is proposed that is based on vulnerability of control measures and moves away from standard definitions of frequency of outcomes. A case study of an Australian rail tunnel is used to identify the limitations of

traditional risk methods. The application of a new seven-step methodology as a quantified approach for the design phase shows how these deficiencies can be overcome during design. The new method is applied retrospectively to an Australian rail tunnel risk assessment, which used current worlds best practice. The analysis demonstrates the limitations of traditional practice once the tunnel was commissioned and operations were subjected to the reality of risk factors. The interaction between rail carriage design, tunnel design, system operations with passengers and external emergency service operations is discussed. The new methodology provides an option that can be used alongside the traditional methods to ensure that the catastrophic end of the risk continuum is included in the design phase and the risk of death and irrecoverable injury is minimised to a much greater extent than currently practised in Australian rail systems and elsewhere in the world. The benefits for an industry that is beleaguered by high profile catastrophic events in Australia and overseas are self - explanatory.

STEPS IN THE NEW METHODOLOGY

The traditional methodology determines an expected number of deaths as a criterion for judging the adequacy of design of tunnel and tunnel ventilation systems but fails to account for problems associated with fire growth and escape. Typically, the artefacts of modern travellers have been omitted from the calculations as shown in the catastrophic fire in the Kaprun ski tunnel in 2000 where a fire in a rail ski lift caused 155 deaths. The myth that has accompanied modern carriage design has been that modern rolling stock has a very low fire risk. In the case of the Channel Tunnel, the traditional calculations of risk that led to the granting of the licence to operate did not provide a protection against the fire of 1996 that caused over 250 million pounds damage and disruption losses. The Channel Tunnel provided a generous safety margin through significant design for redundancy but the controls did not manage to protect the travelling public and the tunnel when the fire occurred. The difference between the design measurement and the operational outcome is quite significant and the new methodology provides an alternative conceptual framework for design so that there is a seamless safety outcome following commissioning of rail transport systems i.e. from design to operation and for the life- time of the system. The set of seven steps (Table 1) shows the logical process whereby risk can be more easily understood by the professions involved in the design process and how the risks can be managed by the operators of the systems once these are commissioned.

CASE STUDY: RAIL TUNNEL IN AUSTRALIA

The new methodology has arisen from research undertaken by the authors between 1990-2001 and is based on observations and analysis of catastrophic disasters across many industries. While traditional risk definitions were found to be credible in describing risk they did not account for the causal factors that operated in the environment of the incidents or the risk factors that combined in any incident. Traditional definitions were not inclusive of the incidents that occurred with the most serious deficiencies being at the catastrophic end of the risk continuum. The definitions encouraged a false sense of security because of the limited reference to a universe of risk factors. When major incidents such as the Channel Tunnel fire occurred the traditional methodology is falsely excused with arguments that the very small end of the high catastrophe risk continuum cannot be calculated accurately. Each of these events is described as an 'exception' leaving the rest of the risk process as a credible method.

Table 1: Steps in risk assessment for tunnel design: Inherent risk to long term consequences.

STEP 1: Define Risk	The first step in the new method is to define risk in terms of inherent potential in the absence of control systems.
STEP 2: Identify the Controls	The identification of existing or new controls includes controls on human factor failures
STEP 3: Identify the Time Dimension	The new methodology which relies on the loss expected in the uncontrolled state due to the presence of consequence and loss factors that enhances the inherent potential in the system shows that the expected loss is dependent on the time spent in controlled states and thus the risk profile is measured
STEP 4: Identify the Human Impact Factors	The new methodology naturally takes account of human decisions that can nullify the anticipated controls and does away with a subjective judgement for risk and can take account of modern societies requirements for good corporate governance
STEP 5: Identify the Impacts	All foreseeable hazards are used. Hazard impacts are defined by utilising the inherent potential of the system rather than limiting the definition to the ALARA format. The severity x likelihood formula is replaced by a multidimensional risk consequence analysis incorporating human factor failures and engineering failures.
STEP 6: Assess the Controls	The adequacy of proposed controls is assessed together with the human factors that lead to degradation of controls.
STEP 7: Include the Post Event Consequences	The buffer that has existed between the design risk and the operational risk following commissioning is rapidly being removed by the Courts with consequences for Directors and managers which may be defined in the near future in terms of 'corporate killing'

ALARA is limited

Traditional methods for design of rail transport systems, adopt an ALARA approach to risk. This approach, involving residual risk, is valid only if the full potential risk of the system under study is evaluated. The traditional methods used in design do not evaluate this full potential, but rely on tacit levels based on agreed criteria.

Various remedial pressures have been applied by the Courts in inquiries and legislation to bring actions against corporations and their directors, including corporate manslaughter. The insurance industry has become rigorous in demanding standards and risk reviews, and regulators have followed this path with reporting requirements from industries and listed companies. However, catastrophic rail accidents keep occurring and the punitive measures and the rigor of regulation do not halt the risk factors. Signal Passed At Danger is an example of a failure that has catastrophic outcomes and has not been brought under control by the most rigorous of measures. These approaches are unlikely to be successful without a proper understanding of how catastrophic risk occurs and can be managed.

Misleading concepts

The classical definition of risk is a combination of severity and likelihood, the former being denoted in monetary loss or death and the latter as a frequency or probability. This type of definition requires subjective criteria against which the level of risk is “judged” adequate or inadequate.

In the broadest sense, risk is the likelihood that factors in the environment will create consequences. Risk therefore measures a change in the state of a system by the consequences or outcomes and these can be both positive and negative.

The risk profile of a system is a measure of the vulnerability of the system to a change in status. Risk is dependent on the controls available to influence the direction of the change in the system. Risk can therefore be quantified in these terms. Adverse consequences range from zero consequences to trivial low impact events through to seriously disrupting events and catastrophic events that cause systems failure. Probability relates to the presence or absence of controls and not to the inherent potential risk that is being measured in a system. Time remains independent and is measured as an infinity of changes to the composition and proximity of all factors in the environment. Consequently frequency is an artificial way of averaging in time when factors may come into contact and can be subsumed within the averaging period being measured.

From the above, the hazard can be defined in terms of potential energy that can be released during an event. This changes the definition of risk to that of an inherent potential in the loss of controls relative to an uncontrolled situation. This definition can be applied to both design and operational phases, ensuring that there is no mismatch between the two.

Consequences

Consider the system shown in Figure 1. The loss in an event can be described in terms of consequence and loss factors that are controlled by prevention and mitigation factors. It is important that the consequence and loss factors are independent of the control factors. The risk can therefore be defined in terms of reduction in loss due to the presence of controls to the loss in the absence of controls.

The traditional design process of Australian tunnels

The fire engineering process (Fire Code Reform Centre, 1996) has become a standard method of establishing the adequacy of fire and life safety provisions in structures. The process involves a fire engineering design brief in which the problem is developed in a qualitative context to establish objectives, define the level of analysis and trial designs.

By identifying hazards, defining fire scenarios and developing acceptance criteria for the structure and occupancy, the process develops an acceptable outcome for the design. There is no logical translation of this process to operational conditions because of the scale of risk factors that are due to the impact of human factors on the design and factors related to the operation of the system. Because the scale of risk is not understood the qualitative discussions that create a few scenarios, do little to prepare the designers for the real operating environment.

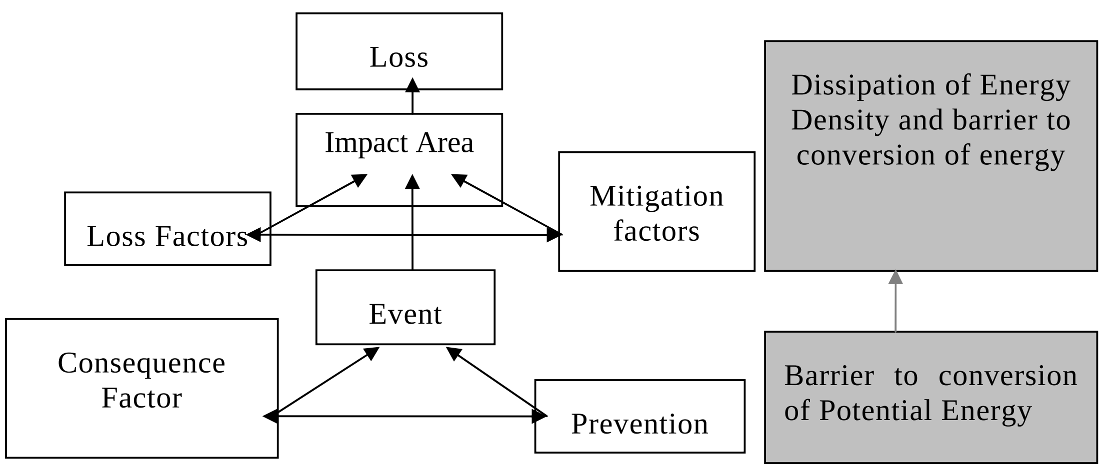

Figure 1: The loss process.

The process creates a false sense of security and the safety requirements are perceived to have been fulfilled by this very limited process. The use of the traditional methods is not disputed as having value in identifying those incidents that are known from history or that can be foreseen in simple risk factor analysis. Some movement towards a more sophisticated approach has developed in computer modelling but the applications of modelling have not been fully understood in the context of defining risk.

Traditional risk management takes place in the context of the wider goals, objectives and strategies of organizations, but this does not logically lead to concepts that are scientific and reproducible in the environment. The thrust of the process is on developing agreed acceptance criteria and the bias is towards risk management in an organisational context. Agreement by groups is also subject to historical forms of bias and influence within the group. The process thus leads to adoption of assumptions that are not tenable for both design and operational phases of the systems. Qualitative methods are unsafe when human factors in creating the design risks create bias and limit the scope of the risk factors.

Fire design assumptions in the Australian tunnel case study

A number of assumptions were used in the design process, which since the rail system began operation, have been limited by the many unforeseen factors in the operational environment. The nullification of these assumptions has important implications for the protection of people during a fire in the tunnel.

The main design assumption was the tunnel would only be used with newer rolling stock that had good fire resistant characteristics. In practice all rolling stock is passed through this tunnel system. The base fire load for the rolling stock was taken as the internal load to the carriage. No external cables or insulation was included in fire design calculations on the assumption that perfect compartmentation existed and that an external fire would not propagate through to the interior. Consequently, the actual values used for the fire load were 2/3rds of the Manufacturers data and included no cables or insulation load. The design assessment did not include passenger's luggage that could be present on the train that serviced transit hubs for air, bus and rail. Luggage adds to the fire load and can alter the rate of fire spread.

In practice high fire loads do occur and the rate of spread is higher than the design used. Another design criterion assumed was that Diesels would not be routed through the tunnel. The first accidental breech of this occurred within a fortnight of the opening of the tunnel. The diesel engine constitutes an increased risk from the nature and quantity of the fuel, which dramatically changes assumptions on fire load. Diesels also have a very different risk profile for incidents and accidents.

Based on the above constraints, the tunnel design assumed that a fire would always be less than 20 MW in size. Consequently a design criterion of 25 MW was used for defining the ventilation required in the tunnel for clearing smoke. That there was no requirement for heat detection or smoke alarm or sprinklers in the tunnel, emergency access and egress at each station would be adequate and no intermediate access would be required for fire services who would utilise station entrances (with the midpoint between the longest distance between stations being 1.2k) followed from these assumptions. The ventilation system was set at a critical velocity of between 2.5 m/s and 3 m/s for clearing smoke from a (maximum 20 MW) fire and implicit was the ability of the driver of the train involved in the fire incident to respond to and communicate with train control on the location and status of the incident and evacuation. This was to be effected by train radio (although there was no rule for radios to be operational) or by climbing down from the cab onto the ballast and proceeding to an emergency phone (which was assumed to be available in clear air).

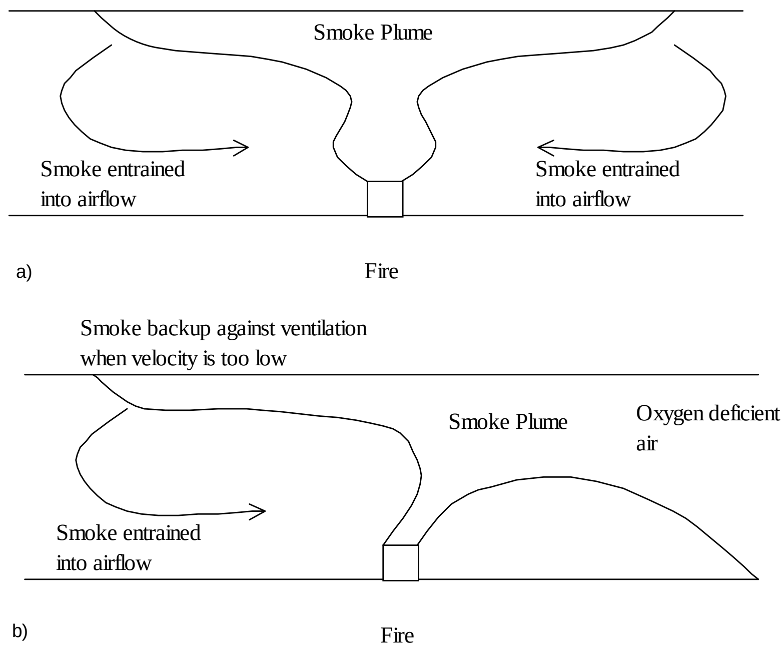

Figure 2: a)Fire development no ventilation b) Fire development with ventilation.

Operational risks: fire and smoke development within a ventilated tunnel

As a fire develops in a tunnel with no ventilation (Figure 2a), smoke rises to the roof and moves away from the fire, cooling, as it gets further away. Due to the heat in the smoke and burnt gases, the smoke tends to accumulate at the highest point and will move up a slope preferentially to moving downhill. Eventually the smoke cools enough to mix with cooler air below it and it is drawn back into the fire at ground level reducing visibility.

When there is a ventilation flow (Figure 2b), the smoke is blown in the direction of the ventilation and as it cools downwind, it will envelop the whole of the tunnel cross-section. The smoke will be deficient in oxygen and may be incapable of supporting life. The smoke will backup against the ventilation at roof level, if the fire is large and the ventilation not strong enough, and when cooled sufficiently will mix with air and be drawn back into the fire reducing visibility.

The ventilation flow around the train in a two-track tunnel will be faster on the clear side of the train and lower on the wall side and above the train due to the blockage. Consequently smoke movement will be complex and will hinder evacuation more in this situation than in a single track tunnel. In both situations the ability to get around a fire to give effective evacuation is questionable.

If the ventilation direction is changed while the ventilation is working then the site will not be clear of smoke until the smoke that was downwind of the fire has been pulled back across the fire. Note that this may also reduce the available oxygen concentration where the passengers are. The ability to evacuate passengers safely is highly dependent on there being uncontaminated air along the evacuation route.

Design of tunnel ventilation system

Figure 3 shows the critical ventilation velocity to prevent backflow for the new rail system as a function of Fire Intensity based on Wu and Baker[2]. There are two important velocities that should be noted: a) the design criteria produces a critical ventilation velocity in the order of 2.5 m/s- there is a slight variation around this value (hence the thick line) as the exact value is also dependent on the slope of the tunnel; b) the maximum velocity required to always clear smoke is about 4.5 m/s. This maximum occurs because once the fire grows to 130 MW, the critical velocity becomes independent of fire size.

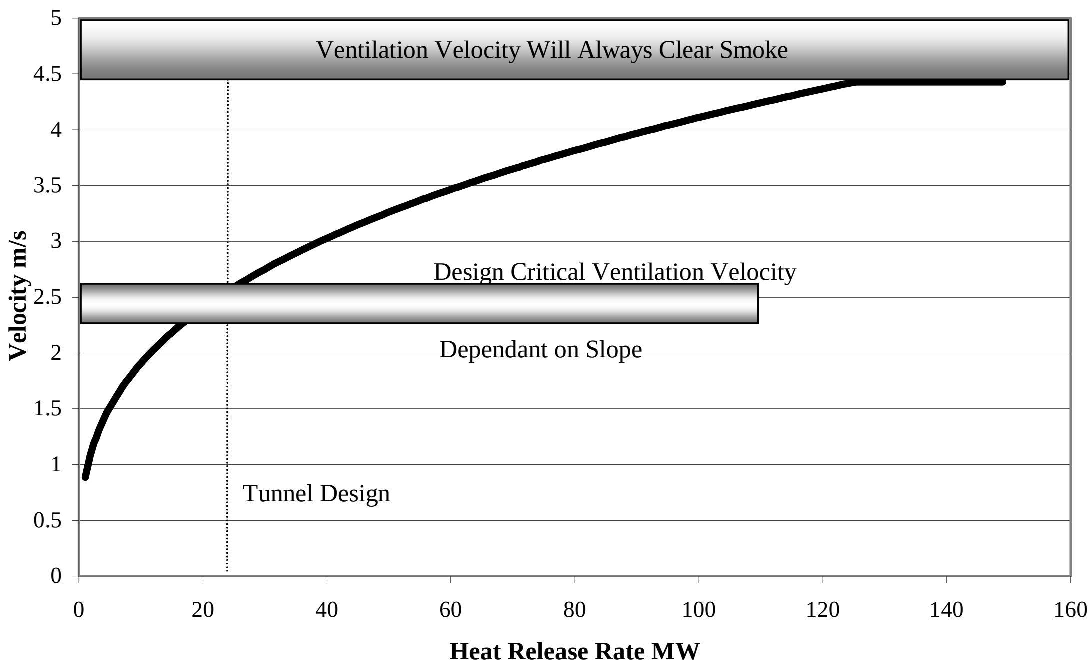

Figure 3: Critical Ventilation Velocities in the new rail system[3] have given the following formula for the critical velocity in a tunnel. $V'' = 0.4.0.2^{\frac{1}{3}} Q''^{\frac{1}{3}}$ for $Q'' < 0.2$ and $V'' = 0.4$ for $Q'' > 0.2$, where V'' is the dimensionless critical ventilation velocity and Q'' is the dimensionless heat release rate.

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Fire load and fire intensity

The data used for design involved considering the fuel within the passenger compartment only. This base data for the fire load in the newer rolling stock are shown in Table 2. The design assessment ignores the luggage that is brought into the carriage during operation. The fire load and other fire performance data for any luggage brought onto the carriages is shown in Table 3. The fire load assumes a value of 19 MJ/kg based on a 20% plastic content (clothes and other objects) and 80% cellulose. The Heat of combustion of cellulose is 16 MJ/kg while most plastics are between 25 and 40 MJ/kg – a value of 30 MJ/kg has been used here. The fire intensity is based on a mass flux from the fuel surface of 10 g/m^2s. This is similar to cellulose although most non-fire retarded plastics are much higher.

Table 2: Fire loads for newer rolling stock per carriage[3].

Rolling stock	**Fire Load (MJ)**
Compartment Fuel Load base case	18302
Manufacturers Data without cable and thermal insulation	28564
Manufacturers Data with cable and thermal insulation	48844

Table 3: Fire properties of luggage.

Luggage	**Mass kg**	**Surface Area m^2**	**Fire Load MJ**	**Fire Intensity MW**
Handbags	2	0.150	1938	0.029
Briefcases	4	0.385	3876	0.073
Suitcases	20	0.540	9120	0.103
Rucksacks	30	0.900	8550	0.171

Table 4: Distribution of passengers and materials in a typical rush hour carriage.

Compartment	**Passengers**	**Handbags**	**Briefcases**	**Suitcases**	**Rucksack**
Crew End	15	4	4	8	6
Upper Deck	61	20	20	4	2
Lower Deck	59	20	20	4	1
2nd End	25	7	7	8	6
Total	160	51	51	24	15

During the rush hours, the newer rolling stock may be packed with 150-200 people per carriage ('crush loading'). If it is assumed that a carriage contains 160 passengers, 13% of whom are travelling to the airport, a typical distribution of luggage within the passenger compartment may be represented by Table 4. The distribution of fuel allows for fire spread from article to article compared with an empty vehicle.

Ignition

There are a number of sources of ignition whereby a fire start can progress into the passenger compartment from outside. Furthermore these types of fire are associated with the motor cabling and control systems and often lead to power loss on the vehicle, ie are the type of failure that will lead to a catastrophic outcome as the vehicle is incapable of getting to a station in the event.

For example, the result of a fire occurring in the power cabinet behind the driver's console and breaking out into the passenger compartment is shown in Figure 4. The fire is spread by the participation of luggage within the passenger's compartment. The fire then spreads throughout this compartment by means of the light fittings, passenger briefcases and handbags left by passengers moving away from the fire, and thence to the upper and lower decks to the end of the carriage. The fire properties of the light fittings have been based on the fire properties of polycarbonate. The model used was developed by piecewise construction of fire spread from article to article and ignored radiative feedback from the developing smoke layer.

Visibility decreases to 2 m in the crew-end compartment and upper deck after 9 min and is less than 1 m at the first flashover after 13 min. The air requirement for this flashover condition can be supplied through the openings to upper and lower levels and ensures continued growth under fuel controlled conditions without the need for breakage of windows, which will also occur. The fire growth calculated is similar to a medium to fast t-squared fire, with coefficient of 0.018 (also shown in Figure 4).

Fire spread in the other compartments is assumed to be spread mainly by left luggage and lighting fixtures. This contributes about 6 MW to the fire in each of the other carriage zones. The seats in the older rolling stock are not as protected as the newer carriages. They will combust and once the material covers have sustained burning the interior material will burn while other material is burning. The exact properties of these materials are unknown since no cone calorimeter studies have been done. The seats contribute about 4 MW to the fire in the upper and lower decks respectively and under 1 MW in the 2nd end compartment.

The level of smoke produced at the time first flashover occurs (13 min), makes the carriage untenable throughout and the fire grows beyond the design specification for the tunnel. If people become trapped in the fire and provide additional fuel to the fire, the fire intensity can rapidly grow beyond 70 MW.

The impossibility of rescue once this has happened was evidenced in the death of 155 people in the Kaprun Ski Tunnel Fire in November 2000.

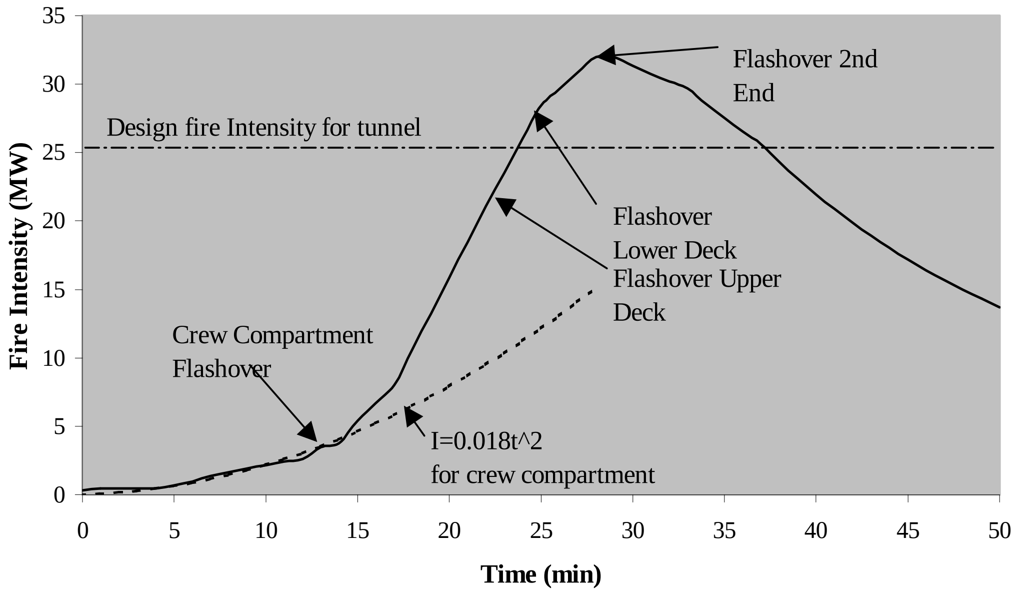

Figure 4: Fire growth in a passenger compartment**.** In these calculations, the seats have been based on the properties of highly Fire Retarded Polymers (Heat release rate of 90 kW/m^2 and mass flux of 6 g/m^{2}s) and Fire Retarded Plywood.

Catastrophic outcomes of fire in tunnels

In the given case study, the consequence factors that effect fire growth in the carriage are the material and compartment layouts and properties under operating conditions. The loss factors are those factors that will affect the ability of passengers to evacuate successfully from this carriage, train and from the tunnel system. These include: status of the mains, battery power, air conditioning and recirculation fans, emergency lighting, inter-carriage and external doors, and condition of driver and guard. In addition, the presence of many of the systems and design features identified as being absent in the case study would provide a range of protective systems that would interact with the fire growth process to prevent or mitigate the otherwise catastrophic outcomes.

Where the tunnel design cannot provide an automatic fire quenching system the usefulness of the fire fighters becomes axiomatic, when the response time to opening a carriage exceeds 18 min. With call out times of fire services and response into a tunnel being somewhat more than 20 min for a breathing apparatus equipped team that has no intermediate access there can be no realistic calculation of rescue, other than self rescue of passengers. Under these conditions the provision of a fail safe ventilation system to create clear air for escape remains the main means of escape. In the Channel Tunnel fire of 1996 the ventilation system was subjected to a series of human errors and did not provide the safety outcome expected within the design parameters.

The fire fighters could not locate the train for a considerable period and by the time they arrived through a positive pressure special evacuation tunnel all passengers had self evacuated (leaving the driver to be rescued).

The size of the fire can be estimated for operational conditions and provides a basis against which the proposed controls can be judged. For example the fire potential of a train within a tunnel and in the open is the same. The risk is different because of the loss and mitigation factors are different in the two cases. The tunnel environment does not allow freedom from smoke compared with the open environment. Once passengers are detrained they are relatively safe in the latter environment compared with the tunnel where they may have to egress in a smoke laden environment with no visible cues on direction. In the Channel Tunnel Fire passengers would not voluntarily move from a non particulate air filled carriage into a black and highly particulate and hot tunnel environment outside their carriages.

CONCLUSIONS

The Australian Tunnel case study has shown how the traditional risk methods which used the worlds best methods at the time of the design, cannot take account of risk changes during operation of the system and hence there is often a mismatch between the assumptions that are made for design and the reality of operation incorporating human decisions which alter the risk of the system. The outcome is a system that traditionally has been accepted in the licensing of tunnels but does not provide a logical process whereby future events have been foreseen and addressed within the design. Therefore traditional risk design methods cannot be described as 'safe'.

By changing the methodology for risk assessment commencing with Step 1, agreeing a definition that admits a universe of risk factors through to the final Step, Step 7 which calculates the post event consequences a risk profile can be constructed that allows for the designers to concentrate on providing controls for the risks and preferably to test the design process in computer simulation and scaled model fires.

The new methodology relies on the loss expected in the uncontrolled state due to the inherent potential in the system that is enhanced by the presence of consequence and loss factors. The expected loss is dependent on the time spent in controlled states and thus the risk profile is measured. The system naturally takes account of human decisions that can nullify the anticipated controls and does away with a subjective judgement for risk and can take account of requirements for good corporate governance by including the last of the seven steps.

The new definitions and mathematics that are discussed are not a 'magical wand' that waves away risk but provide a theoretical framework for understanding why traditional risk management measures may fail. Applications of the new methods alongside the traditional methods will significantly increase the protection of life by expanding the risk factors that are considered in the design phase.

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