A RISK ANALYSIS METHODOLOGY FOR TUNNEL FIRE SAFETY

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ABSTRACT
This paper outlines a fire safety risk analysis methodology developed and applied to a major road tunnel project in Australia. The project name is withheld for confidentiality reasons. The process described is designed to provide appropriate tunnel fire safety design decisions that can be demonstrated as being robust and capable of withstanding third party scrutiny.

The methodology is based on the principles contained in the International Fire Engineering Guidelines¹ (IFEG), the guiding document for performance based fire design in Australia, however, modified for tunnel projects by the authors.

Keywords: risk methodology, tunnel fire safety.

1. INTRODUCTION
The basis of the tunnel fire safety methodology outlined in this paper ensures that the project objectives, fire hazards, proposed trial designs, analysis methods and acceptance criteria are agreed in principle before detailed analysis is undertaken. This paper provides some detail of the rigour that has been applied to a tunnel fire safety design.

2. FIRE ENGINEERING PROCESS
The fire engineering process adopted is similar to the process defined in the IFEG¹. The IFEG¹ is the accepted guideline for the analysis of performance based fire engineering design that has been adopted by Australia, New Zealand, and Canada. The IFEG¹ process is broadly captured in the following steps, and modified for road tunnels:

i. Define the Scope of the Project
ii. Determine the Relevant Stakeholders
iii. Outline the Tunnel Characteristics
iv. Identify the Dominant User Characteristics i.e. the vehicle Driver.
v. Determine the Hazards, and Preventative and Protective Measures
vi. Outline a Trial Design for Assessment
vii. Determine Design Approaches and Methods of Analysis
viii. Determine Acceptance Criteria and Factors of Safety for the Analysis
ix. Determine Fire Scenarios and Parameters for Design Fires
x. Determine the Design Parameters for Design Occupant Groups
xi. Determine the Standards of Construction and Commissioning
xii. Determine Management, Operation, and Maintenance
xiii. Document the above steps in the FEB
xiv. Detailed Analysis
xv. Document the results in the Fire Engineering Design Report(s)

The Fire Engineering Brief (FEB) (refer Step 13 above) is developed in consultation with the stakeholders that agrees the fire safety parameters and trial design solutions. Following agreement of the FEB, the trial design is analysed to access its performance under the agreed fire scenarios. Results are compared to the agreed acceptance criteria and documented in the relevant Fire and Life Safety reports. If analysis identifies a need to vary from the agreed
FEB, the FEB consultation process was revisited and updated to reflect a new trial design, or the Design Fire Scenarios and Acceptance Criteria used within the analysis were re-evaluated. Reasons for varying the FEB could be that the Trial Design changed, or the performance of the trial design under the Design Fire Scenarios did not meet the Acceptance Criteria. At the conclusion of this process, and the completion of the other Fire and Life Safety Reports, a Summary Fire Engineering Report was prepared.

**Figure 1:** Flow Chart of the FEB Process

### 3. PRINCIPAL TUNNEL CHARACTERISTICS

Information such as the tunnel characteristics and use provide a context for design decisions. Key information gathered about the proposed tunnel includes such items as:

i. Tunnel length;  
ii. Number of tubes;  
iii. Number of lanes;  
iv. Location of entry and exit ramps;  
v. Location of breakdown bays;  
vi. Tunnel geometry;  
vii. Vertical and horizontal alignment;  
viii. Uni- or bidirectional traffic;  
ix. Tidal flows;  
x. Construction method and materials;  
xi. Predicted traffic volumes including peak volumes and daily characteristics;  
xii. Predicted daily traffic speeds;  
xiii. Predicted traffic mix;  
xiv. Likelihood of congestion;  
xv. Ventilation system for normal operation (air quality);  
xvi. Ventilation system for incidents (smoke management);  
xvii. Location, type and number of ventilation outlets;  
xviii. Portal emission strategy;  
xix. Non-fire incident management strategy;  
xx. Emergency Services access;  
xxi. Tunnel lighting;  
xxii. Tunnel signage;  
xxiii. Dangerous goods policy including defining which are prohibited;  
xxiv. Communication systems;  
xxv. Evacuation systems;  
xxvi. Egress mechanisms.

### 4. DOMINANT OCCUPANT CHARACTERISTICS

The dominant occupant characteristics are those traits which may influence the behaviour of occupants and users of the tunnel. It includes the age distribution of the population and assumptions on the mental state of vehicle occupants. For the tunnel studied, most vehicles will likely have a single occupant who is alert and able to respond to fire cues and instructions.
provided. Occupants who may not be alert at the time of the incident would be likely to be assisted by fellow occupants. Consideration was given to occupants who may be reluctant to abandon their vehicles or to leave behind their possessions. Occupants in general are not likely to require assistance to move away from an incident or will be travelling with a fellow occupant who is able to provide assistance. Occupants are likely to be strongly affiliated with the driver of their vehicle and take their lead. Vehicle occupants are also likely to be affiliated with other people in their vehicle (e.g. family groups or bus tours). Consideration has been given to the number of disabled users as part of the total number of people using special equipment for mobility impairments. Design considerations need to be cognisant of vehicle occupants not being familiar with the tunnel’s emergency layout or its fire safety systems.

Operators and maintenance staff are assumed to be highly trained and familiar with the fire and life safety features. They are able to provide instructions to allow vehicle occupants to self-evacuate.

5. RISK ANALYSIS

Having determined the principal tunnel characteristics, dominant occupant characteristics and the project objectives, the next stage is a risk based assessment of potential fire scenarios. A systematic review of potential fire hazards was undertaken based on the range of vehicles that will use the Tunnel, anticipated vehicle numbers, and relevant fire statistics.

Table 1 shows vehicle fire statistics for the tunnel under study. The fire frequencies estimated have been used in an event tree analysis to establish credible design fire scenarios for assessment. Based on the fire statistics, severe truck fires have been estimated to occur at a rate of 0.001 fires per year. This is equivalent to an approximate return period of a severe truck fire occurring once every 1,000 years or, for a tunnel design life of 100 years, there would be a 10% chance that a severe truck fire would occur during the life of the tunnel.

Due to the lack of relevant data in Australia, the fire statistics used to estimate the fire frequency were based on European tunnel data generally without the benefit of deluge systems. To adjust for the benefit of deluge systems retarding fire growth and reducing the frequency of severe fires, an event tree analysis was used.

It is also noted that a significant proportion of tunnels in Europe allow bi-directional traffic, and that in an Alpine environment, tunnels have long, steep grades where motor operation is laboured, or brakes can over-heat, tends to bias the data and over-estimate the frequency of fires compared to the flat landscape and uni-directional tunnels as occurs in Australian. This has the effect of over-estimating the fire frequency and provides an amount of conservatism.

<table>
<thead>
<tr>
<th>Fire Frequency</th>
<th>Value</th>
<th>Notes / Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total North Traffic</td>
<td>80,500</td>
<td>Vehicles / day</td>
</tr>
<tr>
<td>Percentage of cars</td>
<td>95.2%</td>
<td>% cars</td>
</tr>
<tr>
<td>Percentage of trucks</td>
<td>4.8%</td>
<td>% trucks</td>
</tr>
<tr>
<td>Car kilometres travelled</td>
<td>12.73</td>
<td>Million km travelled</td>
</tr>
<tr>
<td>Truck kilometres travelled</td>
<td>0.64</td>
<td>Million km travelled</td>
</tr>
<tr>
<td>Car fire = 2 / 100,000,000 km</td>
<td>0.2545</td>
<td>Fires / year</td>
</tr>
<tr>
<td>All truck fires = 8 / 100,000,000 km</td>
<td>0.513</td>
<td>Fires / year</td>
</tr>
<tr>
<td>All truck fires (including damaging and severe)</td>
<td>0.0436</td>
<td>Fires / year</td>
</tr>
<tr>
<td>Damaging truck fires = 1 / 100,000,000 km</td>
<td>0.006</td>
<td>Fires / year</td>
</tr>
<tr>
<td>Severe truck fires = 0.2 / 100,000,000 km</td>
<td>0.001</td>
<td>Fires / year</td>
</tr>
<tr>
<td>Total Fires</td>
<td>0.306</td>
<td>Fires / year</td>
</tr>
</tbody>
</table>
To better understand the types of vehicles that will use the tunnel, the percentages of vehicles for each vehicle type are identified. It is also important to understand the effect of the transport of dangerous goods, if any, through the tunnel. Based on the hazards identified, a Hazard Register should be compiled. The intent of the Hazard Register is to form a foundation for further risk analysis leading to the selection of credible Design Fire Scenarios by agreement with the stakeholders. The Hazard Register also allowed consideration of any additional hazards to be identified. This permits an informed decision by the stakeholders regarding which hazards are considered to be unacceptable and therefore not considered in the design of the Fire Safety Measures. The hazard register also provides information for the Incident Management Plan (IMP) to be prepared by the operator. The Hazard Register should capture:

i. Type of vehicle on fire;
ii. If the vehicle on fire is moving or stationary;
iii. If traffic within the tunnel is flowing, congested or stopped;
iv. The severity of the fire. For the tunnel under study, dangerous goods were prohibited. Therefore, it was important to understand whether diesel spillage was involved;
v. Additional design features provided as a mitigation measure to address these issues.

A fire occurring within a congested tunnel has the potential to expose more tunnel users to fire risks compared to a non-congested tunnel. The following traffic modes were defined and adopted as a means of considering the consequence of congestion in tunnels and its impact:

i. Non-congested traffic: Where traffic is flowing at a speed greater than 20km/hr (5.56m/s) i.e. greater than critical velocity. At this speed, the traffic is generally ahead of the smoke front, and traffic downstream of the incident should continue to drive out of the tunnel and be unaffected by both the incident and smoke;
ii. Congested traffic: Where traffic is flowing at speeds between 5km/hr (1.39m/s) and 20km/hr (5.56m/s). If traffic is moving at a speed which is greater than walking speed, occupants are unlikely to leave their vehicles and evacuate on foot. However, there is potential for occupants to be subjected to some smoke exposure.
iii. Stopped traffic: Where traffic is flowing at a speed less than 5km/hr (or 1.39m/s). This is less than walking speed and it is considered that occupants will be more likely to leave their vehicles and evacuate on foot resulting.

For the tunnel under study, the percentage of time each of these traffic conditions were determined to occur were:

i. Non-congested 95%
ii. Congested 4%
iii. Stopped 1%

These percentages formed the basis of the inputs into the event tree analysis to determine the credible fire scenarios. The smoke control strategy also considered these different traffic conditions to mitigate the risk of smoke exposure to occupants.

6. RISK ASSESSMENT METHODOLOGY

A risk based methodology based on the that documented in Australian Standards\(^3\) and the IFEG\(^1\) was adopted as the framework for assessing the fire and life safety design.

Event tree input considerations were set out within the FEB and agreed with the stakeholders prior to the event tree analysis being undertaken. Event tree construction was undertaken in line with the expected sequence of events occurring during an incident as agreed with the stakeholders. Event tree considerations should include the following:

i. Fire frequency
ii. Operator responses (appropriate or delayed).
iii. Traffic conditions (Flowing, congested or stopped traffic situations).
iv. Fire growth rates (Ultra-fast growth rate or higher).
v. Deluge Impact (Failure of deluge system to control the fire).
vi. System Reliabilities (Failure or part failure of other fire safety systems).

vii. Credible combinations of such events.

The choice of design fire scenarios is one of the most important parameters for the Fire and Life Safety analysis. The traditional process of adopting a single value for the peak heat release rate (HRR) (e.g. 50MW) was considered inappropriate as it can lead to underestimation of conditions in some situations. Similarly, the adoption of a single large value may be excessive and provide expensive and conservative design. Therefore, a method of categorising the design fire scenarios based on the Hazard Analysis was adopted to provide a boundary to the scenarios to be quantified so that the design remains within economic and practical limits; and to facilitate a rational combination of very severe (but low probability) fire events with realistic egress parameters.

The Fire Design Categories are described below:

Base case fire scenarios represent fire scenarios which were expected to occur during the design life of the tunnel (100 years).

High challenge fire scenarios represent rarer but more severe fire scenarios used to test the limits of the design. High challenge fire scenarios were expected to occur at a return period between 100 and 10,000 years. These scenarios included selected system failure scenarios.

Extreme events were defined as fire scenarios that were expected to occur less frequently than a 10,000 year return period and therefore not considered to be credible design cases.

Extreme events have been considered and used to identify operational response procedures and preventative measures to mitigate the associated risks, but have not been evaluated as design fire scenarios.

Extreme events included scenarios which were agreed with the stakeholders to lie outside the practical or economic limits of the design, such as explosion, or BLEVE’s. Subject to the estimation of return periods in the Event Tree Analysis, extreme events could include events such as a deluge failure leading to a severe HGV vehicle fire combined with stopped traffic. Similarly, multiple failures of fire safety systems occurring simultaneously could be an extreme event.

The following process was adopted for the selection of design fire scenarios:

i. Identify the potential fire scenarios based on the Hazard Analysis;

ii. Evaluate the expected return period using an event tree analysis based;

iii. Divide the fire scenarios into the various Fire Design Categories;

iv. Assess potential fire scenarios using the Risk Evaluation Matrix;

v. Review the findings against the Performance Requirements and add any additional Fire Scenarios;

vi. Select the credible Design Fire Scenarios for analysis based on grouping similar scenarios from the more severe Base Cases and High Challenge scenarios;

vii. Review the Hazard Analysis and Design Fire Scenarios with the stakeholders and agree the final list of Design Fire Scenarios.

To assist the evaluation of the Trial Design with the Design Fire Scenarios, a semi-quantitative risk based approach was adopted. The components of the risk assessment approach were:

i. Risk categories (refer Table 2);

ii. Consequence categories (refer Table 3);

iii. Likelihood categories (refer Table 4);

iv. Risk evaluation matrix, modified for the risk categories (refer Table 5);

v. Risk treatment criteria (refer Table 6).
### Table 2: Risk Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Provision of a level of safety for tunnel occupants and users including O&amp;M staff</td>
</tr>
<tr>
<td>2</td>
<td>Provision of a level of safety and access for emergency service personnel during an incident</td>
</tr>
<tr>
<td>3</td>
<td>Limit the impact on assets, including adjacent infrastructure and surrounding road networks</td>
</tr>
</tbody>
</table>

### Table 3: Consequence Categories relative to Exposure Severity

<table>
<thead>
<tr>
<th>Severity Level</th>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Safety of occupants</td>
<td>Unpredictable collapse of tunnel structures within 2 hours of fire incident occurring, or life threatening exposure to radiant heat or fatality remote from area of the fire</td>
<td>Major damage to equipment and/or localised collapse impacting infrastructure above. Tunnel cannot be operated for a significant period (&gt;3 months). Fire that has exceeded 200MW and/or a 2 hr RWS fire curve.</td>
</tr>
<tr>
<td>IV</td>
<td>Incapacitation, or moderate irreversible disability or impairment (&lt;30%) to one or more persons</td>
<td>Predictable local collapse of tunnel structures in area of fire within 2 hours of fire incident occurring, or life threatening exposure or fatality in area of the fire</td>
<td>Extensive equipment damage and/or localised structural damage. Tunnel cannot be operated for a significant period (&gt;1 but &lt; 3 months). Fire ranging between 70-200MW and/or reached a 2 hr RWS fire curve.</td>
</tr>
<tr>
<td>III</td>
<td>Partial incapacitation Objective but reversible disability requiring hospitalisation</td>
<td>Exposure to heat exceeding limits of equipment, or Predictable collapse of secondary steelwork within 2 hours of a fire incident.</td>
<td>Significant localised damage of equipment and structure requires repair and/or the tunnel cannot be operated for a short period (1 month). Fire up to 70MW and/or a 1 hr RWS fire curve.</td>
</tr>
<tr>
<td>II</td>
<td>Discomfort or low visibility Objective but reversible disability which may require hospitalisation</td>
<td>Exposure to heat but within limits of equipment</td>
<td>Significant localised damage of equipment not requiring major repair and/or the tunnel operates at reduced capacity for a short period. Fire up to 30MW and/or a 40 min RWS curve.</td>
</tr>
<tr>
<td>I</td>
<td>Minor Injury, first aid may be required</td>
<td>First aid (minor injury)</td>
<td>Limited localised damage not requiring repair or minor effect on operations. Fire up to 20MW and/or a 30 min RWS curve.</td>
</tr>
</tbody>
</table>

### Table 4: Likelihood Categories relative to Risk Categories

<table>
<thead>
<tr>
<th>Risk Category</th>
<th>Level</th>
<th>Descriptor</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case Scenarios</td>
<td>A</td>
<td>Frequent</td>
<td>More frequently than a year</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Likely</td>
<td>More frequently than every 3 years</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Possible</td>
<td>More frequently than every 10 years</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>Unlikely</td>
<td>More frequently than every 30 years</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>Rare</td>
<td>More frequently than every 100 years</td>
</tr>
<tr>
<td>High Challenge Scenarios</td>
<td>F</td>
<td>Very Rare</td>
<td>More frequently than once in 1,000 years</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>Almost Incredible</td>
<td>More frequently than once in 10,000 years</td>
</tr>
<tr>
<td>Extreme Event</td>
<td></td>
<td>Extreme Event</td>
<td>Less frequently than once in 10,000 years</td>
</tr>
</tbody>
</table>

### Table 5: Risk Evaluation Matrix

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Med</td>
<td>High</td>
<td>High</td>
<td>V High</td>
<td>V High</td>
</tr>
<tr>
<td>B</td>
<td>Med</td>
<td>Med</td>
<td>High</td>
<td>V High</td>
<td>V High</td>
</tr>
<tr>
<td>C</td>
<td>Low</td>
<td>Med</td>
<td>High</td>
<td>High</td>
<td>V High</td>
</tr>
<tr>
<td>D</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>E</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
<td>Med</td>
</tr>
<tr>
<td>F</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
<td>Med</td>
</tr>
<tr>
<td>G</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
</tr>
</tbody>
</table>
Table 6: Risk Treatment Criteria

<table>
<thead>
<tr>
<th>Level of Risk</th>
<th>Recommended Risk Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very High</td>
<td>Risk cannot be justified except in extraordinary circumstances</td>
</tr>
<tr>
<td>High</td>
<td>Drive risks toward the broadly Acceptable Region or demonstrate that the risk is ALARP</td>
</tr>
<tr>
<td>Medium</td>
<td>Residual risk is tolerable only if further risk reduction is impracticable</td>
</tr>
<tr>
<td>Low (and Extreme Events)</td>
<td>Further risk reduction is not likely to be required or would be impractical as resources demanded would be disproportionate to the risk reduction achieved</td>
</tr>
</tbody>
</table>

Definitions:

i. ALARP – As Low As Reasonably Possible (relating to a risk event)
ii. ASET – Available Safe Egress Time (the time provided by the design to allow safe egress in tenable conditions)
iii. Basic Safety Limit – Australian and International tunnelling and transport infrastructure best practice
iv. Basic Safety Objective – ASET greater than RSET
v. RSET – Required Safe Egress Time (the time required by the occupant study for occupants to reach safe egress)

Figure 2: Treatment Strategy

7. ACCEPTANCE CRITERIA

Compliance with the acceptance criteria was considered to demonstrate achievement of a safe outcome for the tunnel. Non-compliance required further fire engineering analysis and could require modification of the fire and life safety tunnel design.

The following limitation or conditions were assumed within the assessment;

Fire Zone: In the area close to the fire, there may be untenable conditions due to heat radiated directly from the fire. The Fire Zone was defined as the area in which radiation from a fire is at or exceeds 2.5kW/m². It will be proportionate to the fire size and may be up to be 30m in length either side of the fire. This is consistent with guidance in NFPA 502².

Survivability in the fire zone is dependent on occupants escaping to a tenable area. For the tunnel under consideration, the time available for escape was extended as far as practical by activation of the deluge system and the tunnel ventilation (smoke management) system.

Deluge Zone: The Deluge Zone is the area over which the deluge system is activated. For the tunnel under study, it consists of a number of zones activated simultaneously to provide coverage over a length of tunnel of 60m regardless of tunnel width. Within this zone, visibility may be compromised due to the application of the deluge.
Table 7: Acceptance Criteria

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Egress Acceptance Level</th>
<th>Technical Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life Safety of Tunnel Occupants</td>
<td>Level I If ASET &gt; RSET preliminary acceptance is achieved.</td>
<td><strong>Step 1, Qualitative Assessment</strong> Qualitative assessment of design fire scenario (ASET versus RSET based on reasoning, i.e. moving versus stopped traffic, and fire size).</td>
</tr>
<tr>
<td>Life Safety of Tunnel Occupants</td>
<td>Level II Broadly acceptable Region</td>
<td><strong>Step 2, Quantitative Assessment</strong> Quantitative assessment of design fire scenario (ASET versus RSET based on calculations). If ASET&gt;RSET preliminary acceptance is achieved. Go to Step 3 to confirm an acceptable risk level for the scenario.</td>
</tr>
<tr>
<td>Life Safety of Tunnel Occupants</td>
<td>Level III ALARP or tolerable region</td>
<td><strong>Step 3, Risk Quantification</strong> Calculate the risk level of the trial design for the design fire scenario. Use the results of Step 1 and Step 2 to inform consequence calculations. If the trial design's residual risk level is LOW, it is considered to be acceptable. Otherwise go to Step 4.</td>
</tr>
<tr>
<td>Life Safety of Tunnel Occupants</td>
<td>Level IV ALARP or tolerable region</td>
<td><strong>Step 4, Risk Acceptance / Tolerance</strong> The trial design's residual risk level has been determined to be a Medium risk. For the trial design to be considered to be acceptable, the following step is required. As the trial design is a performance-based design, specific demonstration that further reduction is impractical must be provided for the risk to be considered tolerable. Otherwise go to Step 5.</td>
</tr>
<tr>
<td>Life Safety of Tunnel Occupants</td>
<td>Level V Generally intolerable</td>
<td><strong>Step 5, ALARP Analysis</strong> If the trial design is a High risk, then demonstrate that the level of risk for the trial design is ALARP. Demonstration of ALARP may require input from several stakeholders. The method to demonstrate an ALARP design will be decided on a case-by-case basis. If the residual risk associated with the trial design is ALARP it is considered acceptable. Otherwise go to Step 6.</td>
</tr>
</tbody>
</table>

8. CONCLUSION

A fire safety risk analysis methodology has been applied to a major road tunnel project which facilitates a rational combination of fire events, and provides a boundary to the scenarios to be quantified so that the design remains within economic and practical limits. The methodology documented provides a framework that may be adopted for all tunnel projects to ensure that design decisions are appropriate and commensurate with the fire and life safety risks.

REFERENCES

4. World Road Association (PIARC)