University of Southern Queensland

Faculty of Engineering and Built Environment

AN ANALYSIS OF HUMAN BEHAVIOUR WHICH CAN CAUSE FATALITIES IN THE BUS AND TRAIN TUNNEL DURING A TUNNEL FIRE EVENT

A dissertation submitted by:

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ABSTRACT

This dissertation develops the analysis of human behaviour which can cause fatalities in the Bus and Train Tunnel during a tunnel fire event. The project aim is to utilise the Root Cause Analysis framework to produce recommendations for the BaT tunnel design with respect to human behavioural fire safety.

Tunnel fire safety is a young area of research. There is much ambiguity in tunnel fire science and includes many unanswered questions such as; human behaviour in relation to tunnel fire emergencies with a particular reference to tunnel operators and emergency services.

The Root Cause Analysis framework was utilised to discover the underlying causes of fatality within a tunnel due to human behaviour. The framework allows for the root causes to be discovered and ensures that recommendations are produced for each event that has the potential to cause loss of life.

Throughout the study publically available information surrounding the BaT tunnel was documented. A literature review was then conducted into the tunnel operations and fire safety within tunnels. Following the literature review, extensive data gathering was conducted to include statistics on historic tunnel fires and case studies that are applicable to the aims of the study. A root cause analysis was carried out pertaining to tunnel fire safety within tunnels. The root cause analysis was conducted upon a specified tunnel fire design which utilizes publically available information along with assumptions that are based on prescriptive measures. The assumed tunnel fire design root cause analysis was undertaken on both the busway and the railway.

The Root Cause Analysis highlighted that both the busway and the railway had identical root causes. The causes of fatality were discovered to be due to Communication breakdowns, slow reaction times, inadequate understanding and inadequate maintenance. The ways recommended to mitigate these risks is through intensive training of all staff, educating the public through marketing and the establishment of sound management within well-defined processes.

There are many limitations involved within the analysis which cause the recommendations to be incomplete. Hence, before implementation of the recommendations the study should be carried out upon complete design data.

The Root cause analysis is an effective framework that could be used to find the causes of risk and failure within the BaT tunnel. The framework was effective in identifying the root causes of the defined scenario. For a more complete analysis, more scenarios should be analysed, with true design data and including the modelling of the ventilation system where possible.

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1 INTRODUCTION

The Bus and Train (BaT) tunnel is a system that incorporates science, engineering, human behaviour and social factors which combine to establish an appropriate systemic risk. One major risk involved with all tunnels, including the BaT tunnel, is the operation of the fire safety system and how human behaviour influences the level of risk associated with fire safety. The question that will be answered throughout this study will be:

"An analysis of human behaviour which can lead to fatalities in the Bus and Train Tunnel during a tunnel fire event"

The aim and scope of the study will be discussed within chapter 1.1 and chapter 1.2 respectfully. Chapter 1.3 will give an introduction to the problem and outline the importance of the proposed study.

1.1 PROJECT AIM

The project aim is to utilise the Root Cause Analysis framework to produce recommendations for the BaT tunnel design with respect to human behavioural fire safety.

1.2 SCOPE

The specifications in Appendix 1 outline the six steps that will be involved to ensure the completion of this study.

1. The first step involves the documentation of publically available characteristics and proposed operations of the planned BaT tunnel.
2. Secondly, a literature review was conducted into the tunnel operations and fire safety within tunnels where particular focus was given towards public transport.
3. Data gathering was undertaken from internationally documented studies and fire safety literature; the data will include historic tunnel fire statistics for both road and rail tunnels and case studies.
4. Two scenarios were then analysed using the root cause analysis framework which pertained to human behavioural impact upon tunnel fire safety, in the context of the BaT tunnels design and operations.
5. The identification of important factors will then be carried out in regards to the human behavioural impacts, upon tunnel fire safety, within the bus and train tunnel.
6. Finally, recommendations will be given in regards to the design of the BaT tunnel based upon the findings from the study.

1.3 BACKGROUND AND IMPORTANCE OF THE STUDY

Tunnels are beginning to play an increasingly important role within the transportation network of Brisbane, Queensland. This is in response to The Queensland Government and Brisbane City Council, whom have made congestion management within South-East Queensland (SEQ) one of their top priorities. The rate of congestion growth in Brisbane over the next ten years is expected to be greater than that of any other Australian capital city (RACQ 2013). The key priorities of the Queensland Government, led by Campbell Newman, are to grow a four pillar economy (including tourism, agriculture, resources and construction), invest in better infrastructure and better planning, revitalise front-line services, lower the cost of living and restore accountability in the Government. The BaT (Bus and Train) tunnel is a project that responds to the Newman Governments priorities.

The BaT project is an innovative solution, proposed in 2013 to help combat the congestion problem within South east Queensland. It involves combining bus and train public transport in a decked, 15 meter diameter, 5.4km long tunnel (see Figure 1 below for a conceptual design). The tunnel will pass from Dutton Park, underneath the Brisbane River and Brisbane's Central Business District (CBD), and finally to Victoria Park. The project will incorporate the construction of three new underground stations located at Woolloongabba, George Street and Roma Street.

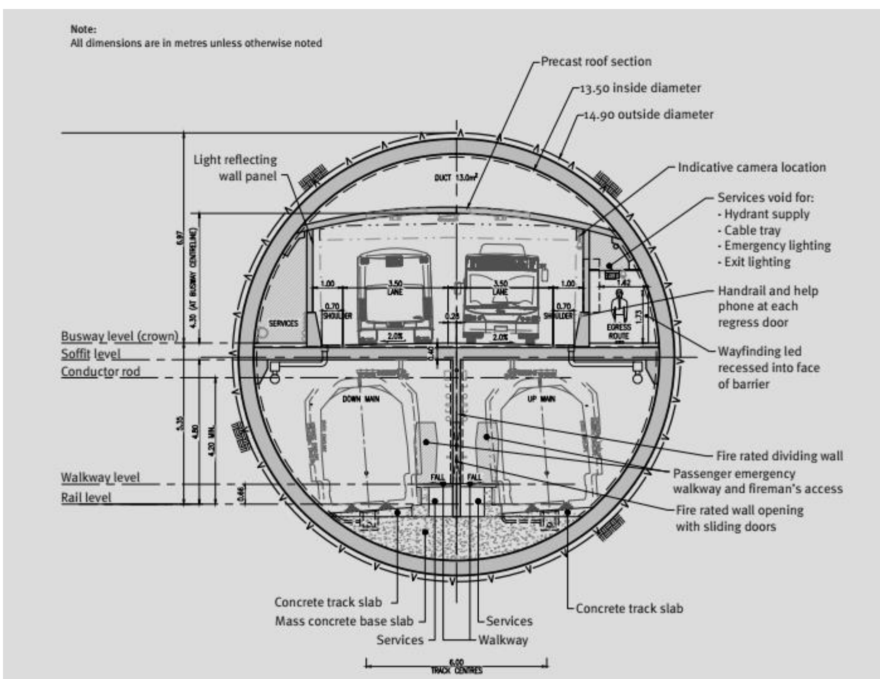


Figure 1 - BaT tunnel concept (DTMR 2014a)

The idea of decked multi-modal tunnels is not unheard of within the world as the Chongming South Channel tunnel, Shanghai will be built to support both motorway and light rail (AECOM 2014).

The BaT tunnel is however unique in the fact that it is designed to support public transport only and a bus only passage way which are rarely seen. The risks associated are therefore relatively unknown.

Fires pose a major risk within tunnels, due to the lack of extensive knowledge within the area and the ability to harm many people from exposure to heat and smoke within a confined space. Tunnel fires have led to many fatalities, structural damage and loss of confidence within the tunnel systems. The manner in which tunnel users act within a tunnel fire event is unpredictable without the development of effective and easy to use systems which are designed to effectively egress humans. Due to the lack of knowledge in tunnel fire safety and the responses humans have to such events it is important to investigate the potential causes and reduce the likelihood to ensure the risk of fatalities is minimised. Historically there have been many devastating fires within tunnels which, if effectively documented, provide interesting insight into the failures of a design due to human interaction. Some examples of historic tunnel fires include, but are not limited to:

- Mont Blanc - 1999 (France/Italy)
- Tauern – 1999 (Austria)
- Kitzsteinhorn – 2000 (Austria)
- Gotthard – 2001 (Switzerland)
- Dague – 2003 (Korea)
- Frejus – 2005 (France/Italy)

The goal of tunnel fire safety is to reduce the potential loss of life through sound designs. Human behaviour and ventilation control has had a significant impact upon tunnel fire safety and the effectiveness of the associated systems. Human behaviour has historically contributed to an unpredictable increase in the risk of tunnel fire safety, which can be illustrated through historic events such as the Huguenot tunnel, South Africa 1994 where passengers egressed from a moving bus and consequently cause head on crashes and increased the severity of the situation (Beard & Carvel 2005).

This study is important as it investigates the risk of bus only passageways and the risk of combining both bus and rail within one tunnel which are both relatively new concepts. The major risk that will be investigated is the human behavioural aspect and the relationship that the Staff, authority figures and tunnel users play within tunnel fire safety. The study hopes to produce results outlining the increased risk that is imposed by the BaT tunnel through human behaviour and effective recommendations to the issues.

2 BACKGROUND

Prior to undertaking a rigours analysis of the BaT tunnels fire safety system in regards to human behaviour, a review of the following topics will be undertaken:

1. Transportation in relation to Brisbane
2. Brisbane public transport stake holders
3. BaT tunnel conceptual design

All data will be collected from publically available sources. The background information is hoped to give context to the difficulties that are currently being encountered within South East Queensland (SEQ) and highlight the need for the BaT tunnel. The public transport stake holders and their operations will be outlined to describe the complexity involved within the Brisbane transport sector and the complexity it imposes upon tunnel fire safety. Finally, the BaT tunnel conceptual design will be explained for use within the analysis of tunnel fire safety.

2.1 TRANSPORTATION PROBLEM IN RELATION TO BRISBANE

This chapter will provide background will be given into Brisbane's transportation problem, the meaning of traffic congestion and Brisbane's increasing population.

2.1.1 Population and Transport problem

Brisbane city is an uncommon case, where there is a high reliability upon bus transportation and houses one of the largest fleets of busses within Australia. The bus fleet consists of approximately 1,255 busses (BCC 2012). In the morning peak hour, 500 of these buses enter the Brisbane metropolitan area and compete for space on the roads with private commuters, taxies and other transportation vehicles. There is unreliability and complexity involved with the Brisbane busway due to congestion, which has caused a trend towards commuters taking private transportation to work. The rail network is nearing capacity along the Merivale Bridge (the only inner city cross river rail) and is causing unreliability in the transportation to and from work.

The Brisbane centre is expected to reach critical capacity soon which is causing a number of social and economic implications. The congestion problem will increase with the growth of Brisbane CBD and the population of SEQ. (RACQ 2013)

2.1.2 Traffic congestion

Traffic congestion, for the purpose of this report, is defined as the interactions between traffic that cause a slow in speed, queuing and/or longer trip times (Ayres 2013). Congestion is also characterised by occurrences such as traffic jams. The capacity of a network is defined by the maximum number of persons or vehicles that can reasonably pass a point, section or roadway within a given time period while acting under prevailing conditions. The units for capacity is generally expressed as vehicles/hour or people/hour. (Ayres 2013)

The operating conditions of roads and other transport networks decreases as the system nears capacity. A qualitative measure is used to describe the operational condition from the perception of the drivers and pedestrians. This measure is referred to as the 'level of service' which is divided in six categories from Level of service A, where a condition of free flow exists and commuters can choose their travel speed, through to Level of Service F, where the flow is forced and queuing and delays are expected. A graph illustrating the different levels of service based on volume flow and speed can be seen below:

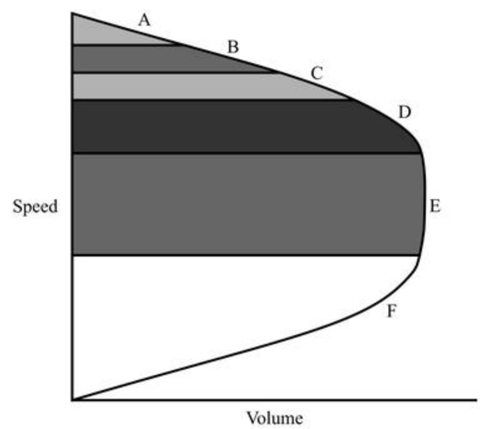


Figure 2 - Level of service(Ayres 2013)

The factors that affect the level of service within a traffic network consist of;

- Roadway conditions
- Terrain conditions
- Traffic conditions
- Driver population

2.1.3 Population Growth

SEQ is one of the primary centres within Queensland, Australia's fastest growing state. The population in SEQ is forecast to increase from over 3 million to 3.7 million, between 2011 and 2021 (DTMR 2013). In year 2031 the population is predicted to reach approximately 4.5 million (DTMR 2013).

2.1.4 Proposal of the BaT tunnel

As highlighted above there is need for an innovative design that allows for increase of public transportation capacity (both rail and bus), while simultaneously reducing congestion and allowing for ease of flow to and from the CBD. This will have a rippling effect on the efficiency of business and economic growth.

The BaT tunnel is one proposed design that will potentially solve the congestion problem within the public transportation system as it allows for the expansion of the bus and rail network simultaneously. The BaT tunnel also allows for transportation to key locations in a more efficient manner.

The key design parameters and benefits of the BaT tunnel will be discussed in chapter 2.3.

2.2 BRISBANE PUBLIC TRANSPORT STAKE HOLDERS

Within SEQ there are three main companies that carry out the operation, maintenance and logistics of the public transport system. These companies include: Translink Transit assiociation, Queensland Rail and Brisbane Transport.

Each of these companies will play a role within the Bus and Train tunnel and the effective operations of the tunnel during normal operating conditions, Incident management by altered operating conditions and Incident response by tunnel closure. Due the involvement of 3 major consortiums it is important to understand their current relationship to discover the changes that need to be made for successful operations and to reduce the likelihood of fatality.

2.2.1 Brisbane Transport

Brisbane Transport (BT) is responsible for the scheduling of bus services within the Brisbane area. BT is under contract by the Translink Transit Authority (TTA) which is a QLD government body. TTA provides public transport to South East Queensland (SEQ).

2.2.1.1 Busway Operations Centre

The Brisbane busway network is managed from the Busway Operations Centre which is currently located in the Brisbane Metropolitan Transport Management Centre (BMTMC). It is a full time facility that manages the busway, busway stations and busway tunnels. Within the center the Busway safety officers are required to be on duty and they also carry out road patrols.

Intelligent transport systems are utilized within the busway system. The control center also operates with CCTV, vehicle detection systems, tunnel operations systems, tunnel alarm systems, and bus station facilities.

An extensive incident management plan has been developed by Translink. The incident management plan involves but is not limited to; Planned incidents, unplanned incidents and special unplanned incidents. Planned incidents involve events that may disrupt the system and still adopt the same incident process. These events include road upgrades, infrastructure repair, cleaning and maintenance and special/sports carnivals. Unplanned incidents involve events such as accidents, terrorist attacks, bomb threats and natural disasters. Special unplanned events require additional attention as they are considered special due to the parameters of the infrastructure.

2.2.1.2 Brisbane Metropolitan Transport Management Centre (BMTMC)

The BMTMC was jointly established by Brisbane city council and Queensland government which incorporated both state and local government road transport operations. BMTMC manages the Brisbane region road transport network along with the busways. The centre works together with Brisbane city council, Translink, and Brisbane transport to deliver effect traffic and public transport conditions.

2.2.2 **Bus way features**

A bus stop is thought of as; points at which a bus will drop off and/or collect commuters along a bus route. Bus stops are intended to be in areas of high visibility and lighting, clearly visible to bus driver and passengers, close to other stops and/or stations to allow for easy transfer between services. The most important operational characteristics of the Brisbane busway is efficiency and safety.

The bus system currently works from:

- Monday – Friday 5.00 am – 12.30 am; and
- Saturday – Sunday 12.00 am – 12.00 am.

2.2.3 **TransLink**

Translink is a division within the Department of Transport and Main Roads whom are responsible for:

1. Mass transit in South East Queensland & regional transit via bus, train, ferry and Tram
2. Demand responsive transit
3. Active transport
4. Taxi
5. Long distance rail, coaches and regional air

Translink partners with a large range of service providers that increases the quality and efficiency for public transport, ticketing, information and infrastructure. Translink facilitates the discussion between state and local government to improve the transport system and infrastructure within Australia.

2.2.4 Queensland Rail

Queensland Rail is responsible for providing adequate rail transport throughout the Brisbane area.

2.3 BaT Conceptual design

To combat the increasing traffic congestion problem in South East Queensland there has been a number of projects proposed including; Cross River Rail, Busway upgrade and the BaT project. The greatest economic benefits are seen from the BaT project as it provides the benefits of both the Cross River Rail and Busway upgrade in a single tunnel.

During the completion of this project the BaT tunnel was in phase B which involves developing the reference design and completing the environmental impact statement. The next stage of the project will focus on procurement then following appointment of the preferred proponent the final phase of early works, detailed designs and construction will begin. A table of the phases and timelines can be seen below in Table 1.

Table 1 - BaT Project timeline (DTMR 2014a)

Phase	Description	Time line
A	Concept Design	2013
B	Reference design and Environmental Impact statement	2014
C	Procurement for construction	2014-2015
D	Detailed design and construction	2015-2020

2.3.1 Benefits of the Project

The BaT project will significantly increase the capacity of bus and rail transportation across the Brisbane River. It will also increase efficiency and reliability of the system within SEQ as it offers higher frequency, faster and direct trips to key locations. The BaT tunnel will reduce private travel by approximately 310,000km per day (DTMR 2014a).

The BaT project is expected to double the capacity of trains crossing the Brisbane river with many other great benefits to the transport system in SEQ. With the increase in capacity of the Merivale Bridge the South and Cleveland Lines have the capacity to grow. The Capacity to cross the Brisbane River will increase from 24 to 48 trains per hour; this also enables the growth of the Gold Coast services. BaT allows for future growth south of Brisbane following 2031 and incorporates planning to add a new line to Beaudesert by 2031 (DTMR 2014b).

The maximum number of passengers on the busway travelling from the south of Brisbane to the CBD will increase significantly. Capacity will increase from approximately 10,400 to 23,100 per hour (DTMR 2013). The capacity for commuters getting to the CBD from the north will increase from 5,200 to approximately 17,900 per hour. The BaT tunnel will ease the bus congestion on the Captain Cook Bridge and allow more access for private vehicles.

Due to the expected increase in appeal for the public transport system, commuters are expected to tend away from private transportation and hence allow for higher levels of service through the city. This in turn will lead to economic and social growth within the Brisbane and SEQ region.

2.3.2 Overview of design

The requirements of the BaT tunnel comprise of stations, tunnels and bridges. It will also involve new and modified tracks, rail and bus systems and the services that compliment them. The design process will take into account construction techniques, logistics, environment and operational issues. BaT is an extension of the Queensland Rail Transit Authority network; it provides new paths for commuters to get to their desired locations. The project demonstrates the need for focus on;

- Fire and life safety
- Ventilation requirements
- Reducing the impacts on surrounding built infrastructure i.e. sewerage lines
- Allowing for future developments
- Construction techniques
- Operating with existing infrastructure/systems

2.3.3 Layout

The BaT tunnel will run from Dutton Park, underneath Brisbane River and CBD, through to Victoria Park in Spring Hill (see Figure 3). There will be stations at Woolloongabba, George Street and Roma Street. The grade and depth of the tunnel will be dictated by the train's maximum gradient restrictions and the structural foundations/infrastructure along with underground utility services.

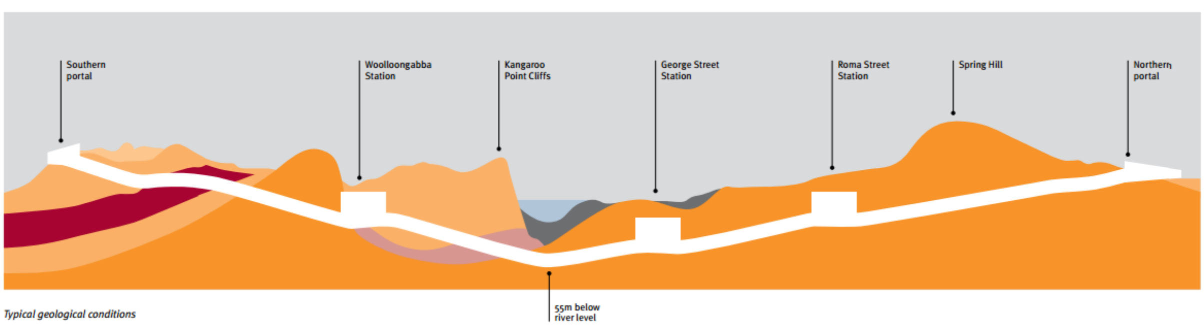


Figure 3 – Potential tunnel alignment (DTMR 2014c)

2.3.4 **Stations**

The new stations will be located at Woolloongabba, George Street and Roma Street. The stations layout will play a key role in the successful operations of system as they will allow for commuters to enter and disembark from the platforms and easily access their desired destination. It is therefore important to consider the following; ease of flow, detailed and easy to read Information systems, appropriate signage, entrance and exits to the station, transportation through the station, dust, noise/vibration caused by the transport system, safety and security and sustainability.

The stations will be designed to cater for the flow of a projected passenger loading for a two-hour peak travel period in both the morning and evenings of 2031. The stations will use escalators instead of stairs where there is a greater vertical rise than 5.4m. When these escalators are the only means for passengers to descend/ascend to the platforms, a minimum of 3 escalators is required, this allows for maintenance in the event of a breakdown. The stations are also required to have Information systems that will incorporate clear and easy to follow instructions. For the stations to remain sustainable the project will incorporate the following initiatives; low energy, capture and storage of stormwater, treatment of emissions, recycled material, long design life with high quality material, minimisation of impact, maximising to density

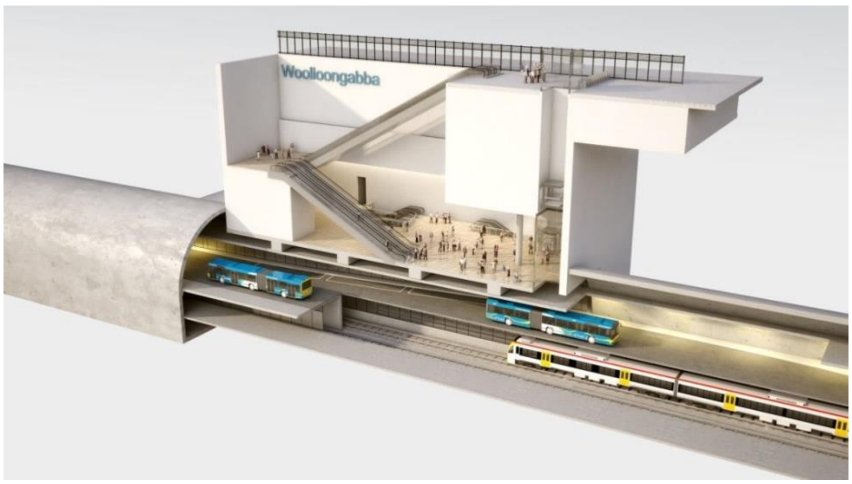


Figure 4 - Conceptual design of Woolloongabba Station

The stations we designed to abide by the following documents:

- Disability Discrimination act (DDA)
- Building code of Australia
- Disability Standards for Accessible Public Transport (DSAPT)
- QLD Rail Station Design Guide
- Queensland Rail Accessibility Signage Manual
- Translink Station Signage Manual

- Brisbane Busway design guidelines

2.3.5 **Ventilation system**

The heat and emissions from the busses will be managed through a ventilation system. The bus fleet operates with high level emissions control systems hence leading to low level of emissions flowing from the ventilation outlets. The ventilation system is also expected to be capable of dealing with smoke in the event of a fire.

Air flow will be controlled by ducts, fans and control systems. The piston effect will be utilised within the railway section in conjunction with fans at the underground stations which are expected to draw the air from the tunnel. Jet fans can be avoided within the busway as overhead ducts will be provided along the crown of the tunnel. (DTMR 2014b)

There will be ingress of air at the tunnel portals and at the intakes. The intakes will be positioned at each of the stations and released through the ventilation systems. Ventilation outlets will also be required at each station and near the southern and northern connection. The proposed ventilation outlets and heights can be seen below in Table 2.

Table 2- Proposed ventilation outlets (DTMR 2014b)

Area	Indicative cross section (m^2) (internal)	Indicative height (m)	Location
Dutton Park (Southern Connection)	15	11	Within Boggo Road Urban Village, adjacent to the railway corridor, east of the Ecosciences building
Woolloongabba Station	35	24	Located at the site of the station building. It is expected that this would be integrated within a future high rise building above the station.
George Street Station	35	25	Located at the site of the station building. It is expected that this would be integrated within a future high rise building above or adjacent to the station.
Roma Street Station	35	8	Located within the railway corridor near to the original Roma Street Station building.
Spring Hill (Northern Connection)	15	8	Located within the railway corridor adjacent to Victoria Park.

3 METHODOLOGY

The methodology for this study will incorporate the Root Cause Analysis framework (RCA). The RCA is intended to identify the root causes of potential loss of life within a tunnel fire in association with human behaviour.

The RCA framework was justified as an appropriate tool for analysis as it allows for the identification of what, how and why a fatality occurred, and allows for the generation of appropriate recommendations. When it is understood why an event occurs recommendations are more credible. RCA are used within industry for a variety of reasons including investigating the cause of a failure, risk analysis, and ensuring that all critical aspects of a design are accounted for. The analysis would therefore be capable of producing recommendations for the consideration within the BaT tunnel design as a result of human behaviour within a tunnel fire. A detailed description and framework for a RCA will be explained within section 3.1 below.

Tunnel fires have occurred frequently in the past and have led to potential loss of life, structural damage and high economic/social costs. The following diagram depicts the process that was undertaken throughout this study to draw conclusions on the human behaviour which can cause fatalities in the Bus and Train tunnel during the event of a fire. This study was undertaken as a desk study and hence no laboratory work was conducted. An explanation of each phase is given below, with reference to Figure 5.

The Methodology of the research will identify the process taken to complete the study, the RCA methodology and its application to the BaT tunnel fire safety analysis and finally the methodology will define what is meant by risk as it is a major element of the study and hence needs to be understood.

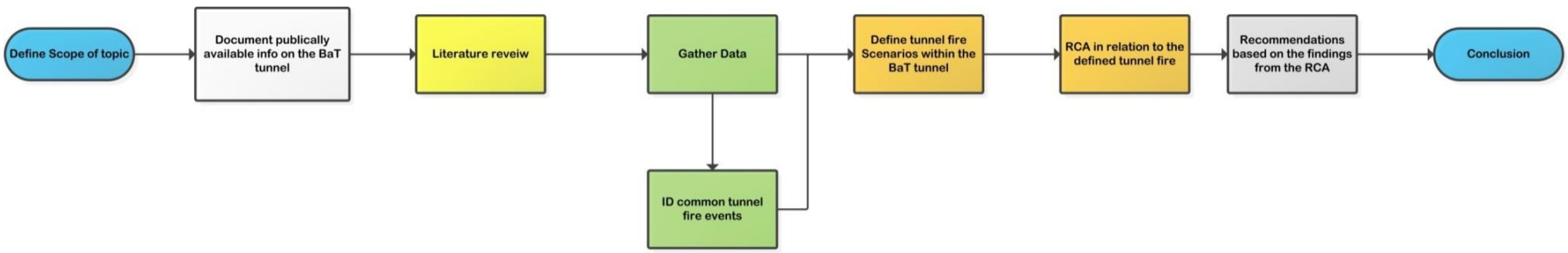


Figure 5 - Methodology

Phase 1

Phase 1 involves defining the topic by means of setting the scope and objectives of the research project. This phase will also involve an explanation into the importance of the study.

Refer to appendix 1, to see the project specifications. The topic in question is:

"An analysis of human behaviour which can lead to fatalities in the Bus and Train Tunnel during a tunnel fire event"

Phase 2

After the scope of the project is defined, sufficient documentation will be provided to explain and define concepts that will be referred to throughout the course of the study. Documentation of publically available information in relation to the BaT project and Brisbane's current transport needs will also be explained. The topics outlined in Table 3 will be thoroughly documented within the respective report section.

Table 3 – Documentation of publically available information

Topic	Description	Report Section
Brisbane Transportation and Demographics	This section discusses Brisbane's population and transportation problems and the impact that this is having upon the public transport network.	2.1
Brisbane's public transport stake holders	This section discusses the major stake holders within SEQ public transport sector and their responsibilities.	2.2
BaT Conceptual design	This section uses publically available information to provide background into the project that will be analysed though out the study.	2.3

Phase 3

A literature review will be undertaken to provide enough information into the background of the problem so scenarios for analysis can be defined. The research will be broad and will include information from all aspects of tunnel fire safety to give a full understanding of the tunnel system and how it interacts during tunnel emergencies. The topics which will be discussed, a description and their respective report section can be seen within Table 4.

Table 4 - Literature review topics

Topic	Description	Report Section
Fire	Fire science, tunnel fires and the effect of fires upon materials will be discussed	4.0
Tunnel Fire risk	Tunnel fire risk outlines the standard AS4825 – 2011 Tunnel fire safety and defines the terms of prevention and protection	5.0
Tunnel Fire Safety Components	The components of tunnel fire safety were considered to be; Ventilation, Human Behaviour, Fire Mitigation, Tunnel design, Emergency Response, Tunnel management, Contingency plans, egress times and Information and control systems	6.0
Operation and Maintenance of road tunnels	The operations and maintenance of road tunnels as per Austroads. This will be split into operation and maintenance and tunnel emergency response.	7.0

Phase 4

Following the explanations of major concepts and undertaking a literature review, data gathering must be undertaken. The types of data that will be collected are the causes of fires, historical events, fatalities and case studies. All data gathering will be undertaken within Chapter 8 of the report. This data will then be compiled into a chart which identifies the commonly occurring incidents within Chapter 0.

Phase 5

Two scenarios will be defined and analysed based upon the BaT tunnels publically available information with regards to the layout and operational procedures. Practical assumptions will be made using data from the literature review and data gathering in the case that it is required.

Phase 5

A RCA will then be carried out following the methodology given below in Chapter 3.1 of the report. The RCA will be used for the generation of recommendations for the design of the BaT tunnel in relation to tunnel fire safety.

3.1 ROOT CAUSE ANALYSIS

3.1.1 Defining the Process

"In many traditional analyses the most viable casual factors are given all the attention" (Rooney & Heuvel 2004)

Casual factors are defined as the contributors which, if removed, would lead to a reduced event or would eliminate such an event. To ensure that all casual factor contributors are identified a Root Cause Analysis will be used in the hope that recommendations can be produced in relation to the BaT tunnel design for fire safety.

A RCA will help identify what, how and why an event can occur. Root Causes Analysis (RCA) is a process used to investigate casual factors, identify root causes and to produce achievable recommendations that prevent a failure from occurring.

In practice, the root causes of events are generally not identified and hence repetitive short term repairs occur and do not solve the underlying issues. The process of RCA involves data collection, casual factor charting, identification of root causes, and recommendation identification. RCA is used within safety, health environments, quality assurance and production impacts and is therefore appropriate for the use within tunnel fire safety. (Rooney & Heuvel 2004)

Defining the term 'root cause' leads to much debate, however for use within the RCA method a 'root cause' will be defined as;

1. Specific underlying causes
2. Can be reasonably identified
3. Management has control to fix
4. Effective recommendations can be generated to prevent the event occurring again

RCA involves four steps. The first step is Data collection. Data collection is vital as without an understanding of the system, all of the the root causes cannot be identified. Causal factor charting is then undertaken, it is a skeleton chart that evolved with information being revealed. Data needs will be identified in this process and hence backfilling will occur. Casual factors can be defined as contributors; if they are removed it would lead to a reduced event or would eliminate the event. Root cause identification then takes place after all casual factors has been identified. Following the identification of root causes recommendations are generated and implemented. (Rooney & Heuvel 2004)

The presentation of the Root cause analysis will be done in a table form such as can be seen in the below in Table 5.

Table 5 - Root Cause analysis presentation of results

Casual Factor	Paths through root cause maps	Recommendations
Casual factors are listed here	Root causes associated with casual factors	Recommendations based on casual factors and root causes

To fill in the table two types of charts will be required. The first chart that will be made will be a skeleton chart; this will identify a sequence of events that could occur. Following the production of a skeleton chart the casual factors will need to be extracted. For the casual factors a Root cause analysis will be undertaken in the form of a chart. Following the production of both charts the findings will be documented in a RCA table such as Table 5. Recommendations will then be generated for each casual factor. It is important to produce recommendations that are able to be implemented.

3.1.2 RCA in relation to BaT

To carry out a RCA into the human behaviour which can cause fatalities in the Bus and Train tunnel during the event of a fire, the scenario in which a fire occurs must be defined. The definition of the scenarios will be explained following the literature review and data gathering and analysis process.

When conducting the RCA the focus will be upon the human systems causes that lead to fatality following the ignition of a fire. The human system is made up of both the humans and the environment in which they interact. The fire is assumed to have already ignited and hence the skeleton chart will be created for events that occur in the lead up to egress. Within this time period there will be many choices that tunnel staff, tunnel users and external bodies such as the emergency services can make. It is hoped that the study will produce recommendations into the ways that emergency response can be better managed and the impacts of human choices can minimise fatality.

Although the RCA method is a good tool to determining the root causes of risks pertaining to fatality within the Bus and Train tunnel there are many limitations to the methodology that will be used within this study. These limitations will be described within Chapter 12.2.

3.2 DEFINITION OF RISK

Tunnel fire safety involves both prevention and protection approaches. Throughout this study, tunnel fire safety will be defined as: "*the ability to protect lives and prevent fatalities through the management of egress*".

3.2.1 **Risk**

There are many risks involved with tunnels. These risks may involve terrorism, structural failure and floods however the main risk that will be focused on throughout this study is the risk of tunnel fires. Within tunnels a number of safety systems have been installed to reduce fire risk. Such systems involve fire detection, ventilation, suppression and alarm systems.

Mitigating risk can be done using prescriptive and/or performance based decision making. Prescriptive regulations give guidelines and codes based on what is seen to be 'best practices'. These regulations have played an integral role within industries and will continue to do so into the future. Prescriptive regulations in relation to tunnels have not been extensively developed in relation to the fire management of tunnels as many unknowns still exist. It is important to realise that being in a world which is constantly changing and growing continuous assessment of risk should be undertaken. (Beard & Carvel 2005)

Throughout the study of the BaT tunnel, both prescriptive regulations and performance based risks specifically associated with the BaT tunnel will be defined and analysed.

3.2.2 **Defining risk**

Tunnels are systems that incorporate a range of components, within tunnels there are two specific types of systems that will be focused upon throughout this dissertation. Human activity system is one which consists of the interaction between people with non-human parts and a functional system is a system which has a purpose or function.

Alan Beard, 2004 considered risk to pertain to three general ideas:

1. Materials should not be viewed in isolation to other parts of the system
2. The level of risk is result of how the system is put together
3. Decision making results in the was a system is constructed

The Root cause analysis will mainly focus upon the human activity system and how tunnel users behave when interacting with the fire safety emergency response system. This being said, the human system cannot be viewed in isolation from other components and hence elements such as ventilation should also be considered throughout the study. Both systems will be analysed to determine the efficiency of the tunnel emergency response system and the human activity associated when the emergency response system is activated.

3.2.2.1 Defining Hazard and risk

'Hazard' is associated with the factors which could potentially lead to/contribute to harm. 'Risk' is associated with outcomes/consequences of a particular type of harm occurring. Risk is usually measured in terms of probability and the degree of harm caused. (Beard & Carvel 2005)

3.2.2.2 Prevention and Protection

Prevention is known to be measures relating to preventing an event occurring, where protection is measures relating to reducing the impact when an incident does occur. (Beard & Carvel 2005)

Prevention and protection will be analysed within the RCA and will focus on means of preventing events that could cause harm following the ignition of a fire. Means of protection will also be analysed and will focus on aspects of the emergency response system that require protection, including human lives.

3.2.3 **Consequences**

There are three levels of consequences that can come out of a tunnel fire. These consist of major, medium and minor consequences. Major consequences are associated with fatalities or severe injuries along with severe property damage and disruptions to the operations. Medium consequences consist of medium level injuries and/or property damage and medium interruptions to the operations. Minor consequences consist of minor/no injuries, minor property damage, and minor disruption to the operations. (Beard & Carvel 2005)

4 FIRE

Fire characteristics are not simple to define and the behaviour is similarly difficult to predict. The means by which fires are extinguished, the length of time taken for fires to 'burn out' and the heat that is extinguished from these fires is therefore ambiguous. However with more testing and monitoring of fires, better understanding of fire science has emerged and hence some estimations can be made.

Each tunnel, including the BaT tunnel, has to take into account fires within the design to ensure a desirable level of safety is reached. It is therefore important to have an understanding of the concept of fire, the heat that can be produced, the toxic gases that are emitted and how it can be applied in the case of mitigating the effects of the fire within the tunnel.

4.1 BASIC CHARACTERISTICS OF FIRE

Fires require fuel, O^2 and heat. Reduction of these components leads to reduction in the fire and eventually leads to extinguishing of the flames. Airflow leads to cooling along with providing additional oxygen to the source. Fires can be enhanced by the addition of oxygen at the fire location. Fire can also be suppressed by cooling the ignition source. (Beard & Carvel 2005)

4.2 FIRES IN TUNNELS

4.2.1 What is a tunnel?

Before discussing the effect of fire within tunnels it is important to firs define what a tunnel is. A tunnel is an underground, underwater way, passage that is enclosed and can be accessed by portals. (Butterworth & Louis 2010)

There is a correlation between the length of the tunnel and the risk associated with that tunnel. There is no method on how to define a short and long tunnel. As a guideline a short tunnel is thought of as one which does not hinder emergency response. (AFAC 2001)

In terms of emergency operations The Australasian Fire Services Council (AFAC) 2001, recommended that a tunnel be classified as long if:

- Tunnel users have no line of site to a portal or evacuation point (AFAC 2001)
- During evacuations it is likely that a fire product will come into contact with users (AFAC 2001)
- When conditions become unsustainable it is likely that firefighting will be carried out (AFAC 2001)

• The maximum useful penetration distance of a breathing apparatus set is not able to support personnel to reach the control point (AFAC 2001)

The BaT tunnel could be seen to be a long tunnel as it fits all criteria given by AFAC 2001. The BaT tunnel has two portals (Northern and Southern). The distance between the two portals is approximately 5.4km long which is required to have evacuation points within the tunnel along with the three additional stations at Roma Street, George Street and Woolloongabba station.

Tunnels are confined spaces. This implies that there is a set amount of oxygen within the tunnel and hence the tunnel fire is assumed to be constrained by the amount of oxygen that is present. This oxygen can be fed to the fire through convection and through the ventilation system.

Fires can be controlled through ventilation, where the fire size is dictated by the amount of oxygen present. Hence there is the ability to reduce the effects of smoke and prevent the fire becoming larger through effective operation of the ventilation system. Alternatively, fires can be fuel controlled where the heat release is governed by the chemical composition of the fuel.

4.2.2 Heat Release Rate (HRR)

The heat release rate of a tunnel is often considered to be the single most important factor involved with the severity of a fire. The HRR (measured in MW) can be calculated based on the airflow **V** (m^3/s), mole fraction of oxygen η_{ox}, the density of the oxygen ρ_{ox} and the heat of combustion for the oxygen ΔH_{Cox} which is generally taken as 13kJ/g (Beard & Carvel 2005). The equation for the HRR can be seen below:

$$HRR = \boldsymbol{V}\eta_{ox}\rho_{ox}\Delta H_{Cox}(MW)$$ (Beard & Carvel 2005)

Hence in tunnels the equation can be approximated to below:

$$HRR = \boldsymbol{V} * 2.73\ (MW)$$ (Beard & Carvel 2005)

4.2.3 Temperature within tunnels

There has been a number of test conducted surrounding fires within tunnels and underground space. Each test incorporates different elements (length, ventilation systems etc.). As a result of a number of investigations occurring into the types of fires that could occur within tunnels a number of time/temperature curves have been developed and are utilised for design purposes. Figure 6- Time/Temperature curve (Promat 2008)Figure 6 illustrates a number of curves on a time/temperature curve, where the tests will be described below.

- ISO – Cellulosic curve is a standard fire test that is used for elements of construction based on national standards
- HMC/HC – is applicable to small petroleum type fires which have much greater HRR than materials such as wood burns. The HC test should be used when there is potential for small hydrocarbon fires to occur. HMC is a modification of the HC test
- RABT ZTV – this test was developed in Germany, within this test the reinforcement should not reach 300 degrees Celsius.
- RWS – This test was developed in the Netherlands and is based upon the worst case scenario; a fuel tanker with $50m^3$ load which is a fire loading of 300MW lasting up to 120mins.

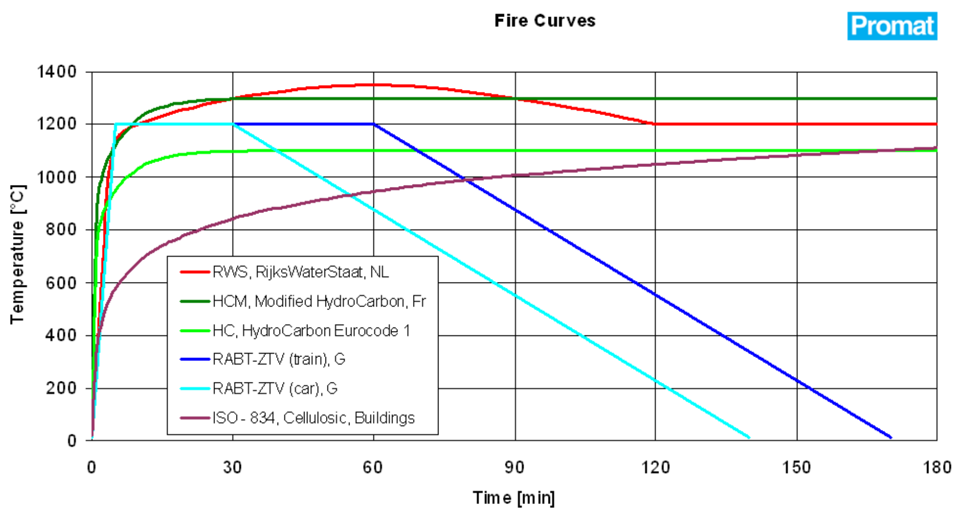


Figure 6- Time/Temperature curve (Promat 2008)

Within AS4825-2011 guidelines are given as to which fire resistance should be used in accordance to the traffic type. A table of the guideline is seen below in Table 6. However for both bus and rail tunnels a fire curve of RABT-ZTV (rail) should be utilised for structural elements. The structural elements should be designed to resist 60-120 minutes. Hence the BaT tunnel as a minimum should be designed to resists RABT-ZTV (train) fires.

Table 6 - Design Criteria for fire resistance AS4825-2011

DESIGN CRITERIA—FIRE RESISTANCE TIME-TEMPERATURE CURVES RELATIVE TO TRAFFIC TYPE AND TUNNEL STRUCTURE

Traffic type	Structural elements (immersed, unstable ground or critical elements)		Separating elements	
	Fire curve	Duration, min	Fire curve	Duration, min
Road	RWS/HCinc	60–120	AS 1530.4	60–120
Bus	RABT-ZTV (rail)			
Rail	RABT-ZTV (rail)			

It is known that all tunnels differ in design and hence a fire will vary depending upon the characteristics. The characteristics affecting the fire are gradient, cross sectional area, time/duration of the fire, location of the fire, and ventilation speed. (Promat 2008)

Within a tunnel there are three distinct phases which are described in Figure 7. These consist of fire growth, fully developed fire and Decay. There is a flashover period where fires grow to temperatures of around 900-1200 degrees Celsius. (Beard & Carvel 2005)

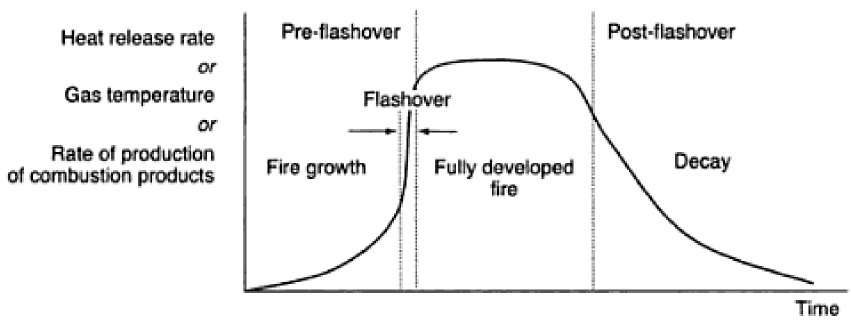


Figure 7 - Phases of a typical fire(Beard & Carvel 2005)

4.3 EFFECT OF FIRE ON MATERIALS

4.3.1 **Concrete**

Concrete is a material that does not contribute considerably to the fire load. High temperatures caused by fires and its associated effects, generally lead to a phenomenon known as spalling which can undermine the integrity of the structure, this is especially true when reinforcement is exposed and burnt.

Prestressed concrete elements can become detached and lead to a loss of bearing capacity/effect.

Spalling is a chemical reaction caused by the sudden increased temperatures inflicted upon the concrete due to a fire. The water molecules that are bound within the concrete are released, this leads to an increase in volume and hence the concrete will begin to flake/combust. An example of spalling can be seen in Figure 8. The high temperatures associated with fires can also cause a change in properties of the aggregate which could cause a decrease in volume and hence crumbling of concrete. Spalling can also occur when there is a difference in expansion between the concrete and the reinforcement bars.

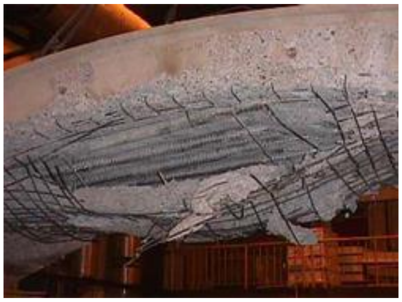


Figure 8- Concrete Spalling

Spalling can cause a serious economic risk. It has been shown that concretes with increased strength under normal conditions are also more susceptible to spalling.

Tunnel fires can exceed 1300 degrees in just a few moments due to the confined spaces and thermal shocks that are imposed upon the structure. There are many time/temp curves to choose from (Figure 6) however the lower the curve the lower the cost however it could also induce a higher risk.

5 TUNNEL FIRE RISK

Tunnel fires are generally more severe than fires that occur within the open, this is due to the confined space and its ability to trap heat and smoke. Fire habits within tunnels depend on characteristics of the tunnel i.e. length, ventilation, traffic volume. Hence preventative, protection and responsive actions for fire safety should be considered within the design phase of the tunnel. (Beard & Carvel 2005)

The level of risk for tunnels is generally based upon the design characteristics of the tunnel along with the operational procedure linked to the tunnel. Hence within the BaT tunnel there is need to define elements of both the operational and structural system to develop appropriate recommendations about the risk involved.

5.1 AS 4825 – 2011

The objective of any tunnel should be to design for a sufficient level of fire safety which will minimise loss of life, allow for effective operation of emergency response and protect adjoining property and third parties. AS4825-2011 is a performance based standard that provides guidance on the design, system selection, construction, management and emergency response procedures and hence ensures safety is a key component within the design of tunnels.

This standard will be used throughout the study and will be used to make assumptions about the design of the busway and the railway.

5.2 PREVENTION

Fire prevention methods exist to ensure that ignition does not occur. Some measures to prevent fires within tunnels include (Beard & Carvel 2005):

- Reducing ignition sources and hot surfaces
- Using fire retarding materials where possible
- Separating fuel and ignition sources where possible
- Reducing the likelihood of spontaneous ignition

Some techniques that tunnel operations/designs employs to prevent tunnel fires is to avoid ignited fuel sources entering the tunnel through the use of information and control which is described within Chapter 6.6. Other techniques involve the prevention of tunnel items from becoming ignited. (Beard & Carvel 2005)

5.3 PROTECTION

Fire protection includes passive and active fire protection. (Beard & Carvel 2005)

5.3.1 Passive

Passive protection relates to features of the tunnel itself. It relates to properties of the tunnels construction which act to suppress the spread of fire and smoke, these elements of the tunnel are generally there for life.

There are generally four measures of passive fire protection:

- Structural Protection
- Compartmentalisation
- Passive means of escape
- Envelope of protection

Structural protection pertains to measures such as protecting against the effects of heat and the transfer to the structural elements. Compartmentalisation relates to division of the structure which adds to the fire and smoke resistance. Passive means of escape are the fixed aspects which assist in the need for escape from the tunnel. Envelope protection deals with methods of protecting the tunnel from external factors that may lead to the ignition of a fire.

5.3.2 Active

Active fire protection is operational in the event of a fire. The protection requires a form of communication to people and/or equipment about the presence of a fire. Active measures have a greater concern with preventing smoke spread as opposed to preventing fire spread. Fire brigades and emergency services are included within the active protection approach.

5.4 RISK ANALYSIS

A risk analysis is usually undertaken prior to the design of the tunnel. Hazards and risks should be identified within the analysis. Limited incidence with tunnel fires has occurred and hence there is a significant lack of information surrounding methods of analysing the risk. The outcome of a single fire could change the risk profile of the entire tunnel such as the Mont Blanc fire. (AFAC 2001)

When results from the risk analysis have been developed the level of risk should be accepted by a relevant authority. The level of risk associated with the design should consider the following before being accepted:

1. Life safety of motorists and other occupants

2. Life safety of emergency service personnel
3. Facilitation of the emergency services personnel to undertake emergency response.
4. Limit the impact upon property, business interruptions and environmental effects

The main risk in tunnels is the vehicles that are travelling within them. The fires are usually caused by electrical defects, overheating of brakes and other defects. Statistically, there are fewer fires caused due to collisions, mechanical defects and maintenance work within the tunnel than by vehicle defects. (AFAC 2001)

It was found that urban tunnels tend to have higher fire rates than alternative tunnels. Of the tunnels that were observed approximately 40% did not have any fires. The final observation from PIARC's study was that the rate of HGV (heavy goods vehicles) fires was higher than that of the passenger cars. (AFAC 2001)

A trend seems to be noticed with tunnels where there is an increased risk of a fire occurring where heating within the brake and engine is common (steep grades, tunnel after steep hills, and long downward slopes). Upon the initial opening of the tunnel there is an increased risk of fire. (AFAC 2001) Within the BaT tunnel the grade will be dictated by the grade of the rail and hence there will not be significant overheating of brakes and engines within the tunnel.

It can be said that the level of tunnel safety is a result of three main contributing factors:

1. Tunnel design
2. Tunnel management
3. Emergency response

5.4.1 Tunnel design

Tunnels designed with bidirectional flow differ from tunnels which involve unidirectional flow. The design flow direction within the tubes dictates the ease of emergency response to access the site. Tubes which have traffic flowing in both directions have a higher likelihood of crashes and the ability for locomotives to cue in both directions. Cross passages and service tunnels increase the likelihood of passenger survival up egress however they are not fool proof, the St Gotthard tunnel for instance had 11 fatalities despite the passages within 2011 (Beard & Carvel 2005). Consideration should also be given to the days taken to service the tunnel and the logistics/consequence of diverting traffic. Length, cross section and other dimensions are important parameters involved with the rate and level of heat and smoke build up. The dimensions also play a role in determining the feasibility of having emergency walkways along the side of the pathway. It is hard to change the major design once the tunnel has been constructed and hence consideration of all aspects must be taken into account.

The fixed installations have an impact on the effectiveness of the system and the ability for people to egress and emergency response to ingress. The ventilation system is used for exhaust, and supply of fresh air. Systems have also been put in place purely for use within an emergency. Natural ventilation should be factored into the emergency response in addition to mechanical ventilation systems. Other installed goods that need to be considered is firefighting equipment, phones, alarm systems and other sensory equipment.

5.4.2 Tunnel management

Within tunnels, management is required within operations, traffic and engineering. One of the most critical of these is traffic management. The main factors that need to be considered with tunnel traffic management include volume, speed and vehicle type. The heat output of buses is much higher than for cars, where it was estimated that a tunnel fire within Oslo, Norway in 1996 experienced heats of around 36MW after 6-10 minutes (Beard & Carvel 2005). Fires involving HGV have been known to reach heat outputs of approximately 100 – 300 MW (Beard & Carvel 2005).

5.4.3 Emergency response

Emergency response is the final stage at providing safety within the tunnel. There are two categories of emergency response:

- Normal emergency services
- Special tunnel emergency teams

6 TUNNEL FIRE SAFETY COMPONENTS

Before analysis of the BaT tunnels fire safety system can be conducted it is important to first understand the components that are considered within tunnel design to ensure fire safety. Within tunnels there are a number of elements that need to be considered. Each of these elements has an impact, to some degree on emergency response. A tunnel should consider the emergency response system during design and pay particular attention to the facility ventilation, human behaviour, and fire mitigation. (Beard & Carvel 2005)

It is important to consider the following when designing tunnels and drawing from historic events;

1. All tunnels are different (length, cross section, construction, terrain, gradient, ventilation conditions, traffic flow etc.)
2. Tunnels are a dynamic (changing) system
3. New material should be considered and both advantages and disadvantageous looked at
4. Economics always plays a role within design selection unless there is reasons not to

6.1 VENTILATION SYSTEM

A ventilation system within tunnels is generally required to remove the contaminants produced by traffic. It involves the circulation of air and can occur using a natural effect, traffic induced piston effect or by mechanical effect. The ventilation system should be chosen as the most cost effective for construction and operation to produce an acceptable level of risk. Within tunnels it is also important that there is adequate smoke control, heated gas control, environments suitable for evacuation and rescue. Emergency ventilation can be natural (using the buoyancy effect) or mechanical. (Modic 2003)

Three types of ventilation operational modes exists; normal, emergency and temporary ventilation. Emergency ventilation should remove smoke and hot gasses in the event of a fire. The ventilation system should allow an evacuation environment which has low temperatures and is relatively smoke free. (Modic 2003)

A ventilation study should be conducted which will lead to development of a fire ventilation plan. This should account for spread of fire, smoke, toxic gases and heat in the tunnel. Different types of ventilation systems should be considered to find a suitable system for the tunnel in question. The ability for the ventilation system to suppress fires should be included in the study (Thompson & et.al 2011).

Provisions of fire safety has been known to depend upon the length of the tunnel (definition of tunnel length can be found in Section 4.2.1). Guidelines have been established by several countries relating to the adoption of natural ventilation in relation to the length of the road tunnel – refer to Table 7. In early civilisation natural ventilation was utilised, whereas today more stringent measures need to be adopted along with the invention of steam engines/combustion engines.

Table 7 - Countries guidelines on the use of natural ventilation in relation to the tunnel length (AFAC 2001)

Country	Safety length	Condition	Guideline
Germany	350m – 700m	Below safety length	Safe without emergency exits and mechanical ventilation
France	**Urban** – 300m **Non Urban** – 500m **Non Urban** – 800m-1000m (if traffic <2000 vehicles per day per direction)	Above safety length	Smoke control measures are required
UK	400m	Below Safety length	Allowed to adopt natural ventilation with justification
Netherlands	-	-	Decide by risk analysis
USA	240m	Below safety length	Allowed to adopt natural ventilation

Natural ventilation is seen to be inconsistent as it relies mainly upon the meteorological conditions. The main condition having an impact upon natural ventilation is the pressure difference between the two tunnel portals, this is caused by elevation, temperature and wind differences (Beard & Carvel 2005). For more reliable means of ventilation mechanical systems are installed into tunnels (Beard & Carvel 2005). One of the first recorded mechanical ventilation systems was within a Holland Tunnel in the 1920's. This was in response to the increasing concern over the combustion engines within road vehicles.

Ventilation systems can be categorised into two large groups; Longitudinal and Transverse.

6.1.1 Longitudinal Ventilation

Longitudinal ventilation is applied most often to metro and railway tunnels (Beard & Carvel 2005). Within longitudinal ventilation systems the air flows longitudinally through the tunnels. The purpose is to move clean air into the tunnel and push heated and polluted air through and out the opposite portal. Refer to Figure 9 and Figure 10 below.

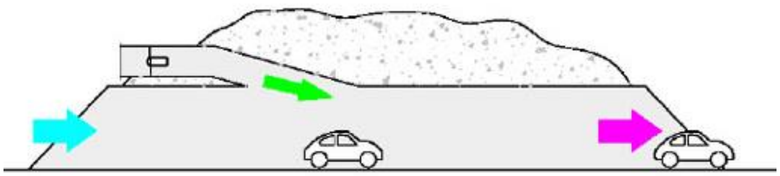


Figure 9- Injection type (Saccardo nozzle) Longitudinal Ventilation example (Kusta 2012)

Mechanical Longitudinal ventilation is referred to as any system that introduces or removes are from the infrastructure. Hence the system creates longitudinal airflow through the tunnel. There are two main forms of longitudinal ventilation; Injection-type and the employment of Jet fans.

The injection type system is most common within rail way tunnels. It involves the use of a Saccardo Nozzle which induces the high velocity injection of air into one end of the tunnel as a low angle to induce airflow through the tunnel. Refer to Figure 9 above.

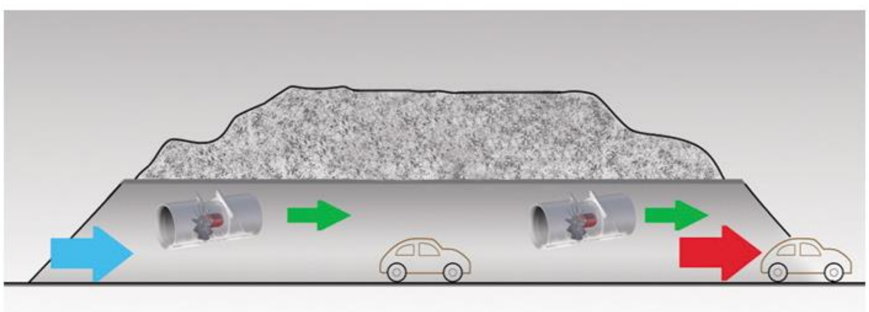


Figure 10 - Longitudinal ventilation example 2 - Use of jet fans (Kusta 2012)

Jet Fan longitudinal ventilation systems (Figure 10), involves a series of fans installed along the tunnels roof.

An alternate means of longitudinal ventilation is the use of two shafts located close to the centre. One shaft takes in the exhaust and the alternate supplies air (Figure 11). This ventilation system will lead to a reduction in temperature and air pollution at the shafts due to the extraction of air and supply of air at ambient condition. (Beard & Carvel 2005)

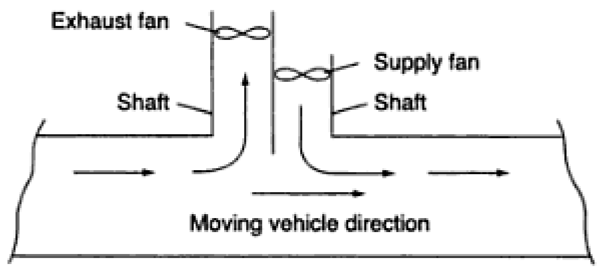


Figure 11 - Two-shaft longitudinal ventilation (Beard & Carvel 2005)

6.1.2 **Transverse**

Transverse ventilation involves the uniform distribution of air along the length of the tunnel. Three forms of transverse systems are employed within industry; Fully Transverse, Semi-transverse (exhaust) and Semi – transverse (supply).

Fully Transverse ventilation systems (refer to Figure 12*),* involves an exhaust duct that runs the full length of the tunnel which is complimented with a full length supply duct. This system was developed in New York and has been primarily been used for long road tunnels (Beard & Carvel 2005). It has however been shown that this type of ventilation system does not have the capacity to control smoke and heated gasses within a large fire (MTFVTP 1995).

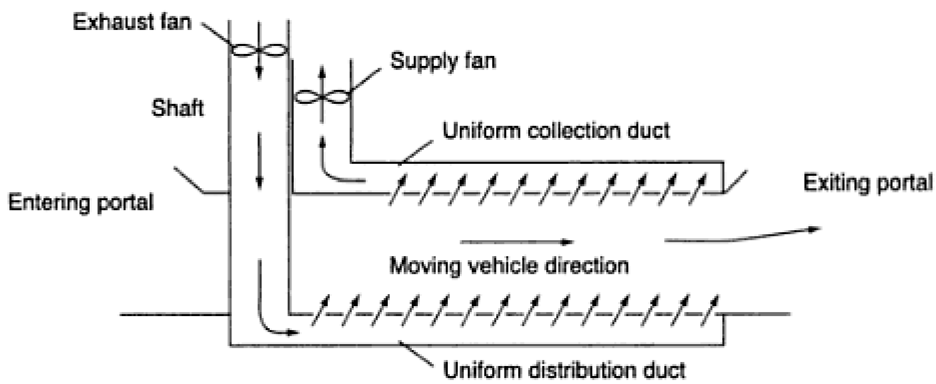


Figure 12 - Fully transverse ventilation system(Beard & Carvel 2005)

*Semi-transverse ventilation systems (*Figure 13 *and* Figure 14*),* provide uniform distribution or collection of air over the entire length of the tunnel. There are two forms of semi-transverse systems; exhaust and supply.

1. Exhaust semi-transverse system, will produce a finite amount of exhaust (pollutants and temperature) at the exit portal. In the event of a fire the smoke will be extracted through the system (Figure 14).

2. Supply semi-transverse systems (Figure 13), will cause a uniform level of pollutants and temperature. In the event of a fire the smoke will be diluted by the supply system. However it is preferred to have a reverse cycle within the supply ventilation system to help with fire-fighting efforts and ensure the air enters the tunnel through the portals. (Beard & Carvel 2005)

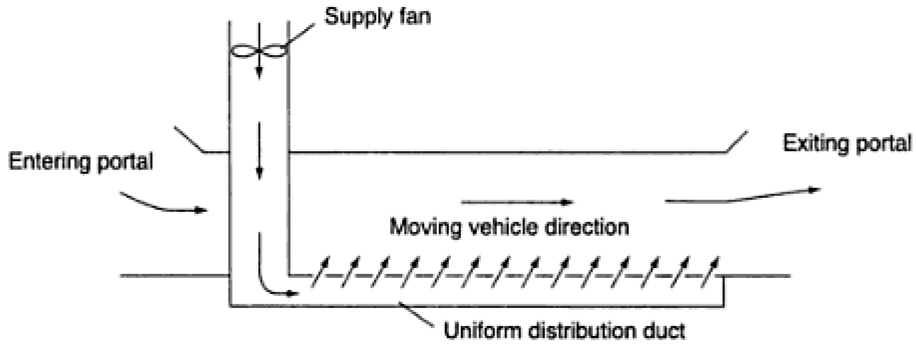


Figure 13 – Supply semi- Transverse ventilation system(Beard & Carvel 2005)

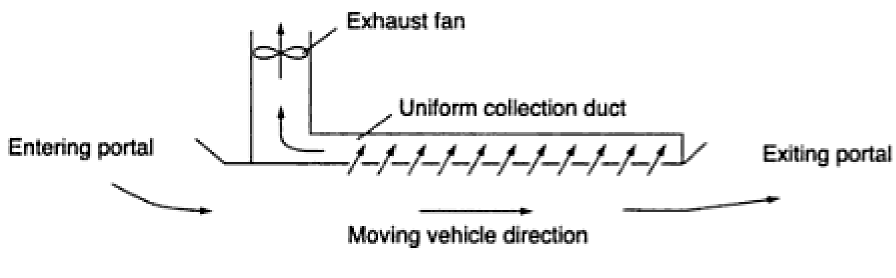


Figure 14 - Exhaust semi-transverse system(Beard & Carvel 2005)

There have been circumstances where a combination of systems are utilised to increase the extraction of pollutions throughout the system and allow for improved fire life safety. An example is the Sydney Harbour Tunnel which utilises both longitudinal and transverse ventilation is present.

6.2 VENTILATION COMPONENTS

Tunnel ventilation systems are made up of many components; fans, dampeners, motors and controls. Each of the components will be described below.

6.2.1 **Fans**

Ventilation fans are utilised within tunnels to create a continuous airflow. The rotary blade within the fan creates a force on the air and therefore maintains the airflow and increases the pressure. There are two types of fans; axial and centrifugal.

1. Axial flow fan (Figure 15)
2. Centrifugal fan

Axial flow fans (Figure 15) are generally parallel to the impeller shaft. They are designed to withstand the maximum pressure and temperatures that are expected within tunnels. Reversing the flow of air through the fans is possible by reversing the motor rotations.

Centrifugal fans have rotating wheels. Air enters parallel to the fan shaft and is discharged at 90 degrees to the shaft.

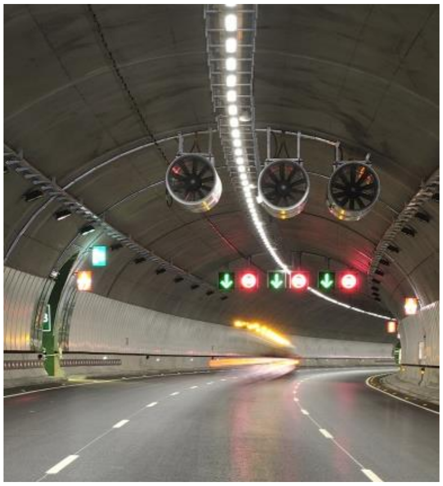


Figure 15 - Axial flow fan

6.2.2 **Dampers**

Dampers primary function is to control the flow of air in the ventilation system. The dampers can provide resistance within the system and hence vary the flow rate of the air. In emergencies dampers can be used to vary the exhaust and inflow to control the fire level. There are sliding blade dampers and rotary blade dampers.

6.2.3 **Motors**

Tunnel ventilation fans are generally driven by motors. The motors are selected based on fan speed and its design requirements.

6.2.4 **System control**

The control of ventilation systems can be manual or automatic and operated locally or remotely (see section 7.2 for more information)

6.3 HUMAN BEHAVIOUR

When designing the fire safety system, human behaviour must be taken into account. The behaviour during a tunnel fire is similar to that of other buildings (Kobes et al. 2010). The most important aspect of tunnel fire safety is therefore considered to be the ability for egress in the event of a fire.

One major difference between road tunnel fires and building fires is that humans are generally reluctant to exit their vehicles and leave their belongings behind.

There are three critical factors that are involved with survival in the event of a fire; the fire characteristics, human features and the building design and operations. The role of a person has a large contributing effect on the behaviour of the individual during the event of evacuation.

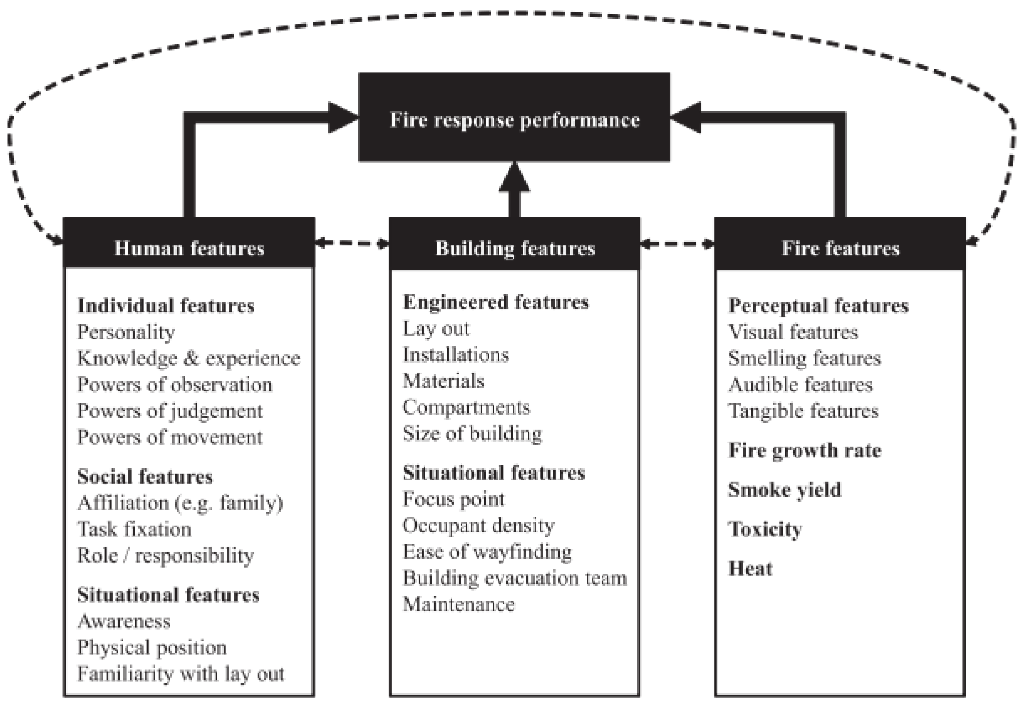


Figure 16- Variables affecting human performance in fires (Kobes et al. 2008)

The nature of the fire is a major component of fire response performance. The fires critical characteristics involve the smoke, toxicity, heat and growth rate (as seen in Figure 16).

The engineering features of the building are relevant to the fire response performance. This involves the layout, installations, materials, fire compartments and size. The accessibility and signage relating the emergency exits play a big role in egress. Effective exit was discovered to be approximately 60 persons/meter/minute (Kobes et al. 2010). It has also been revealed that within buildings, emergency exits that are not used in everyday situations will also not be utilized during an actual emergency. A survey conducted by Kobes et al. (2010) showed that out of 400 cases of fire escape, 92% of people were unaware of the signage that pertained to emergency response (Kobes et al. 2010). People were also found to ignore fire alarms, and generally walk slower when exposed to fire effects.

Figure 17 - Sydney Harbour Bridge stop signals (Burns et al. 2013)

The most crucial moment in tunnel fire response is the first moments after the incident has occurred. Within three fatal tunnel fires in Europe it was found that motorist ignored red signals, stop signs and alarms and continued to proceed through the tunnel, this lead to fire spreading and increase mortality. The Sydney Harbour Tunnel in Australia used this study to employ a new strategy to stop motorists entering the tunnel which involves projecting stop signals onto a cascading wall of water (Figure 17).

6.3.1 **Stages of Behaviour within tunnel fires**

In the event of a fire it has been seen in historical events such as the Tauern Tunnel, Austria 1999 that the smoke spreads quickly through the tunnel. In this particular case smoke was traveling through the tunnel within 2 minutes. The incident reviews associated with the Tauern tunnel showed that smoke was a contributing factor to the human behaviour. (Fraser-Mitchell & Harters 2005)

6.3.1.1 Recognition

The first stage of tunnel fire safety is the recognition of an existing fire. The recognition period has a focus upon the communication. Communication can be done between different levels of the authority hierarchy and should be open, direct, short and to the point. The communication system should be reliable.

The communication between the authorities and the members of the public is important to persuade the passengers of the importance to behave appropriately. For effective response the users must be convinced that an emergency is genuine. There are sometimes difficulties in conveying messages due to language barriers, background noise and disabilities. There have been problems with lack of information to tunnel users during the wait periods.

Communication can also be carried out between members of the public. This communication is restricted to verbal and visual communication. Public interact with authorities to raise alarms and ask for assistance.

6.3.1.2 Response

Non-egress activities are generally undertaken by authority figures which are in response to their roles and training. Occasionally the public engages in efforts to fight fires. The cause for the public engagement is unknown and thought to be either due to the responsibility felt by the tunnel user or due to taking of responsibility as an "authority figure". Non-egress activities involve attempts to smoulder the fire, rescue operations and keeping the passengers informed. (Fraser-Mitchell & Harters 2005)

Egress activities can begin with group formations. Building fire research has shown that social groups stay together. The tightest group is generally family groups. Social affiliations may also form larger groups; these types of groups generally cause higher fatalities as they are generally disorganised and less receptive. In the case that a group leader emerges and acts quickly within the large group, social affiliations can be a huge benefit.

There is a large reluctance to leave baggage behind, many bus and train passengers have been known to try and bring their baggage with them. It has been observed that baggage tends to slow tunnel users by approximately 50%. (Fraser-Mitchell & Harters 2005)

6.3.1.3 Exit/direction choice

Within tunnels the authority figures are generally familiar with the layout of the tunnel and would consequently use the tunnel exits. The direction will usually be in the opposite direction to the tunnel fire. (Fraser-Mitchell & Harters 2005)

6.3.2 Roles and Behaviour

There are a number of people that can be present within a tunnel, they may include:

- Members of the public
- Tunnel staff (ventilation control, station staff etc.)
- Members of the rescue and emergency response team
- Bus drivers
- Rail staff

The response of the control room has a carryover effect on the delay before the emergency response and rescue teams are notified. The control room can delay the evacuation of tunnel users depending upon the system that they have in place. Some patterns of the behaviour displayed depending upon the assumed role will be outlined below.

Members of the public do not seek out information and generally wait for it to be delivered to them. They generally can only communicate face to face or via gestures. The formation of groups is possible if instructed to do so, otherwise only the pre-existing groups will huddle. Disabled personal generally receive help or have helpers with them. (Fraser-Mitchell & Harters 2005)

Authority figures take action and investigate prior to positively reacting to a situation. They tend to fight fire and give instructions/orders to the public. The staff search and rescue/inform those in need and generally assist those who need help.

The fire services will travel towards the fire in attempt to extinguish and help the individuals that they encounter along the way.

6.4 FIRE MITIGATION

Fire configuration is determined by a combination of parameters; fire surface height, tunnel height, fire size and the flame height.

Longitudinal ventilation systems utilise jet fans to push smoke to one side of the tunnel which can be effective in the event of a small fire. When airflow is too low to deal with the influx of smoke from a fire within the ventilation system, smoke may flow against the air flow intended. This phenomenon is known as 'back-layering' (refer to Figure 18). This causes a flow of smoke in both the upstream and downstream direction. This indicates that the velocity of the longitudinal ventilation system should be greater than a determined critical value which will prevent the back-layering of smoke. (Modic 2003)

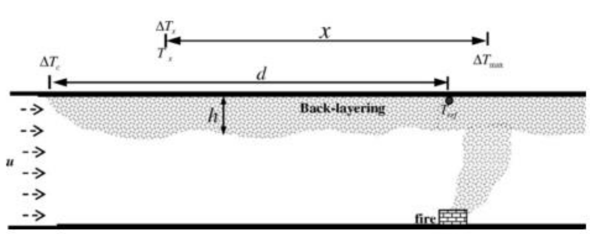


Figure 18 - Back-layering (Hu, Huo & Chow 2008)

Within ventilation controlled fires it is important that excess oxygen is not supplied. If air flow is too high infernos can be created such as in the St Gotthard tunnel fire 2001. Figure 19 shows the use of ventilation to extract the smoke while still providing oxygen for the tunnel users to escape.

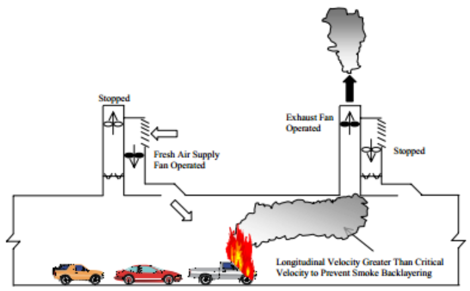


Figure 19 – Ventilation control - (Kwa 2014)

6.4.1 Fire detection

The first signs of a fire are smoke and heat. These effects of fires are potential deadly for tunnel users as it can potentially fill the tunnel. The ability to detect smoke, heat and flames early by tunnel operators can result in earlier activation of smoke extraction system and add to the likelihood of users to escape. The damage of fires increases with the time taken to intervene.

6.4.2 Fire design

Design fires are used to decide upon the criteria of the tunnel and to test the ability of the tunnel parameters and operations. A number of design fires should be chosen to represent different fire scenarios within the tunnel. Design fires should consider a number of different parameters, some possible parameters to considered consist of but are not limited to; Length and width of the tunnel, construction material, operation of the tunnel and availability of the emergency exits.

Within the Root Cause Analysis method there is a need to define a design fire which allows for the analysis of the human behaviour in relation to the design fire. Given a different scenario there would be different reactions and hence justification of the events must be carried out.

There is a distinct relationship between tunnel length and the design fire which should be considered with defining the parameters of the design fires. The relationship includes the following factors:

1. Increasing fire frequency as a result of the tunnel traffic
2. Fires can develop without effective control
3. Increasing airflow in the tunnel to establish an escape route and the consequences of this action
4. Tunnel profile and gradients

The BaT tunnel is a long tunnel which involves high traffic flow during peak hour traffic and will increase with the increasing population. As the tunnel is long it is important that the ventilation is controlled in an effective manner during emergency response. It should be such that the fire smoke can be minimised to allow egress and emergency services to ingress and not fuel the fire with oxygen. Hence the ability to extract smoke through an overhead duct while receiving oxygen from the portals is a good design which should be investigated further.

Design fire can consist of a number of scenarios including collisions, pool fires (usually involve DGV's and flowing liquid spill fires) and incidence involving one driver.

6.5 EGRESS TIMES

Egress times were estimated via the following formulae by Beard and Carvel (2005):

$$RSET = T_{CUE} + T_{PRE} + T_{mov} + T_{QUE}$$

$$T_{CUE} = time\ for\ alarm\ activation\ following\ detection$$

$$T_{PRE} = pre - movement\ time$$

$$T_{mov} = Time\ taken\ to\ move\ from\ location\ at\ the\ time\ of\ cue\ to\ the\ nearest\ exit$$

$$T_{QUE} = residual\ quaeing\ is\ the\ time\ taken\ in\ the\ event\ of\ quing\ at\ the\ enterance\ of\ the\ exit$$

6.6 INFORMATION AND CONTROL

Within society, reliance on technology is evident. Some reasons for this trend include the increased reliability, increased productivity, reduced costs and more efficient systems that come with technology use. Therefore, it is no surprise that most modern systems, such as tunnels, utilise an industrial control system. SCADA (Supervisory control and data acquisition) is an industrial control system that provides for the effective monitoring, gathering and processing of data. It can also send out commands instantaneously to components of a system at the decision of the operator.

Information and control systems are important within tunnels as they provide for efficient and effective monitoring. The system has the ability to monitor multiple activities and ensures that attention is drawn to components of the system that is not operating at its full potential.

An outline will be given about SCADA and its application to tunnels bellow.

6.6.1 Supervisory control and data acquisition

SCADA (Supervisory control and data acquisition), allows for the supervision and monitoring of real time data within a larger system such as a tunnel (Daneels & Salter 1999). The SCADA system takes inputs and produces outputs through a number of interfaces that are outlined below in Table 8 - SCADA interfaces. SCADA systems are generally easy to integrate with other automated systems such as the Digital Addressable Lighting Interface (DALI). The system can simultaneously handle a large number of inputs/outputs (over 100 thousand). SCADA systems provide reliability and efficient performances. (Daneels & Salter 1999)

Tunnels are one example of where SCADA systems can be utilised. Tunnel SCADA systems are generally operated out of a control centre. The size of the tunnel will dictate the location of the control centre. Control systems within tunnels also contain emergency detection and response systems. The considerations of what possibly needs to be included within the SCADA system for a tunnel may include but is not limited to (Innovation2integration 2014):

1. Lighting
2. Ventilation system
3. CCTV
4. Fire detection system
5. Fire deluge system
6. Tele control
7. Energy
8. Public announcement system
9. Incident detection system
10. Communications systems
11. Traffic control systems
12. Radio and Wireless

Figure 20 - Example of tunnel control room

Depending upon the size and design of a tunnel, operations can form a complex system. Complex systems require real time data analysis. Data is exchange between all systems allowing for the desired/programmed transactions to be carried out automatically or via user commands. SCADA is known to be used within tunnel control centres. Within a SCADA system there are a number of interfaces including those seen in Table 8.

The SCADA system can pre-empt decisions based on particular inputs. An example of the systems pre-empt decision making process would involve changing ventilation velocities based on the number of cars entering the tunnel. To install a successful SCADA system firstly the physical infrastructure must be properly understood along with the desired outcomes to ensure that correct results occur relevant to certain situations.

The SCADA system should be able to link to all automation devices and sensors within the tunnel.

Table 8 - SCADA interfaces

Interface	Definition	Example/picture
GUI (Graphical user interface)	The GUI allows users to interact with the screen via clicking and dragging as an alternative to entering text in command lines (Terms 2014)	Windows and Mac are GUI-based
PLC (Programmable Logic control)	Used for automation and electromechanical processes. Used to control machinery via taking inputs and giving outputs based on information provided via inputs.	Amusement rides utilise PLC's
RTU (remote terminal unit)	RTU's primary role is to collect data and transmit the data back to the control centre. No processing and decisions are made by the RTU based upon the data provided.	Used within Meteorology stations
HID	The HDI (Human interface device) is the interface that allows interaction with humans.	Computers.
CCTV	CCTV (closed-circuit television) is a TV system that is monitored and is generally utilised for security.	

6.6.2 **Intelligent Transportation systems (ITS)**

Intelligent Transportation Systems (ITS) purpose is to create a safer, more efficient and cleaner transportation system. It incorporates satellite navigation systems, variable message signage, toll systems and traffic and road information systems. It allows for in-vehicle systems, vehicle-to-vehicle, and vehicle-to-infrastructure. One major advantage to infrastructure is the use of real time data that can be accessed for the use of traffic volume estimation.

7 OPERATION AND MAINTENANCE OF ROAD TUNNELS

Sound Operations and Maintenance is vital to the delivery of sustainable infrastructure and ensuring that objectives are met (such as design life). Over the life span of tunnels there will be many changes to parameters which influence the design of the tunnels. Some changing parameters may include the traffic volume, new fuel sources for vehicles (electric cars), external conditions such as weather, or the commissioning of new rolling stock within railway tunnels. The importance to have flexible and innovative designs which account for future flows and design parameters is therefore highlighted. These changes may also have an effect upon the operations and maintenance of the system and hence should be continuously revised to increase the efficiency and lower risks. Due to the constant changes associated with tunnels, they are often referred to being dynamic in nature. Learning from historic events also plays a significant role in defining the operations and maintenance of a tunnel.

Operation and Maintenance (O&M) manuals are key instruments used to conduct efficient and effective O&M throughout time. The following information is aimed at giving a more in-depth explanation of what expertise Australia has within tunnel operations and maintenance and how it relates back to tunnel fire safety. Hence the following will include O&M definition, defining a tunnel, single modal tunnel operation guidelines, Quality of O&M along with Interchange O&M.

The following information provided will be used as a background to the findings from the Literature review and Analysis and Discussion of Results.

7.1 OPERATIONS AND MAINTENANCE

In context with this dissertation we will be focusing on the design, monitoring and control of emergency response operations locally, domestically and to an extent internationally and how that relates back to the BaT tunnel operations (Ceder 2007). However the following information will mainly focus on the expertise that is available in Australian as official publications from Austroads, which is developed to improve Australian transport outcomes.

Maintenance and Operations generally complement each other as they are ongoing and rely on the counterpart for success within the system (Butterworth & Louis 2010). Maintenance involves both corrective and mitigating actions to ensure the equipment, machinery and/or system involved within the transportation network is running at acceptable operating standards and the maximum operating life is achieved.

7.1.1 O&M Manuals

Operation and maintenance manuals should be completed after the construction of a project however, before the commissioning of the project. The manual should be completed in joint collaboration between the owner/developer, the design team, the contractor, the property manager and any other involved party. (Butterworth & Louis 2010)

When developing the manual it is important to identify key design elements, systems and materials. For many projects, and components of projects, a majority of the operation and maintenance manuals will currently exist for similar designs and hence will only require assembling and/or modifications to suit specific circumstance.

The BaT tunnel has similar components to many tunnel designs around the world and hence the BaT tunnel O&M manual can extract pieces of information from tunnels around the world i.e. SMART tunnel, ØRESUNDSBRUN, and even the Clem 7. However, as the BaT tunnel will be used solely for public transport and Brisbane has unique relationships between the transportation systems (refer to Chapter 2.2) new relationships may have to be developed to ensure that all components of the operation runs effectively.

7.1.2 Single modal tunnel operations

Tunnel operations consider three main situations (Butterworth & Louis 2010):

1. Normal operations
2. Incident management by altered operating conditions
3. Incident response by tunnel closure

Butterworth and Louis, 2010 states that Australia's single modal tunnel operations have been considered to incorporate:

- Monitoring of traffic flowing through the tunnel
- Managing Signage and announcements
- Emergency response (roadside emergency phone calls)
- Liaison with emergency response teams
- Control of tunnel equipment and safety equipment
- Dispatch support vehicles, incident response personnel and roadside assist vehicles
- Implementing emergency response procedures

To ensure the design life span of transport infrastructure safe, reliable and effective operation and maintenance is required. This is especially true in circumstances where the tunnel is a part of a larger network where the effects of an emergency can transfer throughout the system. Tunnels that have limited options in terms of egress for commuters upon entering a tunnel also pose particular concerns for the operation and maintenance (Butterworth & Louis 2010).

The BaT tunnel is expected to connect with the existing network of tunnels within Brisbane through realigning the current road network i.e. easy access to the Legacy Way tunnel from the Northern Portal. This means clear signs will be required to ensure that the network can be easily navigated by the public transport system. Upon entering the BaT tunnel the only option to exit the tunnel will be the opposite portal. Hence it is important to ensure that the tunnels have effective O&M and a sound emergency response system in place.

The Austroad guide to road tunnels, 2010 encourages operation guidelines to consider:

- Management and control of systems associated with traffic management (i.e. tolls, vehicles entering and exiting the facility)
- Management of tunnel plant and equipment (i.e. sump pumps, air conditioning)
- Ready entrance into the tunnel
- Network interface and impact
- Maintenance facilities

The size and capacity of the tunnel in question will dictate the level of operations required. The operation of tunnels could consequently range from being operated as part of a larger network through to having a dedicated control room with continuous surveillance.

Continuous surveillance will be required for the BaT tunnel, not only because it is a large tunnel which will have a high frequency of commuters entering the tunnel but also because it is a major component of the Public transport system where timely operation of the bus and train services is required.

People and documentation is important to the organisational structure surrounding the management of road tunnels. People involved within the organisational structure are required to be familiar with each role. Minimum requirements include;

- An organisation chart. This chart should show the titles and relationships between members on the O&M team
- Position descriptions should be readily available which states the operational authority/levels of access.
- Flow charts showing the relationship between the O&M organisation and external stakeholders, such as client, other traffic management agencies, the police service, emergency services and other relevant authorities.

- Supporting interface protocols agreed by the relevant parties.

To ensure the consistency of operation of a tunnel the processes should be known to all involved within the organisation’s structure and to all relevant stakeholders, the minimum standards for road tunnels involves (Butterworth & Louis 2010):

- traffic management plan and traffic control procedures
- an incident management plan and incident response procedures (including protocols for intervention by police and emergency services)
- an asset management plan and maintenance schedule, standards and procedures
- a safety management plan
- an environmental management plan
- a training management plan
- system and equipment operation and maintenance manuals

Risk is generally reduced in the design and planning stage of the road tunnel. For existing road tunnels the reduction of residual risk is concentrated upon, it is therefore important to carry out operations that will reduce the likelihood of a particular event occurring.

To ensure consistency between documentation, the operations documents should be written to comply with:

- AS/NZS ISO 10005:2006
- AS ISO 10013:2003

These standards will be described in more detail in Quality of O&M within section 7.1.3.

Continuous communication should be maintained between the stakeholders of the road authorities, tunnel owners and operators to allow for, where possible, a consistent approach to tunnel operations and a consistent approach to driver information.

7.1.2.1 Operations objectives

Single modal tunnel operators aim to achieve certain objectives. These objectives will depend upon the characteristics of the tunnel. It is very likely that the characteristics of the tunnel will change throughout the lifetime of the tunnel (i.e. the usage of the tunnel) and hence operations may change over time. Typical objectives of tunnels include:

- Safe passage through the tunnel
- A high level of service leading to reduced travel times
- Reliable travel time

- Fast and effective incident response
- Maintain air quality (within the standard range)
- Maintain external air quality within prescribed limits
- Improve the performance of the road network
- Information to road users is clearly, timely and effectively distributed and displayed to road users
- Coordination and collaboration with road network stakeholders

The implementation of a traffic management plan that incorporates a safe and effective traffic route that utilizes the bigger road network should be agreed upon by the owner/operator and the relevant road authorities. The requirements for traffic management and control equipment are set out by Austroads.

7.1.3 **Quality of O&M**

When creating the operation and maintenance objectives it is important to ensure all documents are written clearly and concisely. All procedures should be documented and written to an acceptable standard.

7.1.3.1 AS/NZS ISO 10005:2006

This standard 'Quality management systems - Guidelines for quality plans' outlines the procedure for the development, review, acceptance, application and revision of quality plans. Within the document advice is given on identifying the need and inputs of a quality plan. Below in Figure 21 the process that should be followed to allow continual improvement of the quality plan is seen.

Within tunnels continuous improvement to the operations is required and revisions can be made through clearly defined processes. As tunnels are a constantly changing environment (i.e. the traffic volume, density etc.) with constantly changing parameters the management system must be revised to maintain the quality. Within the BaT tunnel if new services are rolled out in the Bus Network or similarly upon the rail network there may be cause to add to the O&M manual or to change the operation or maintenance of the tunnel. It is important to improve on the documentation to ensure document control and the ability for information to be available in the case of turnover of staff.

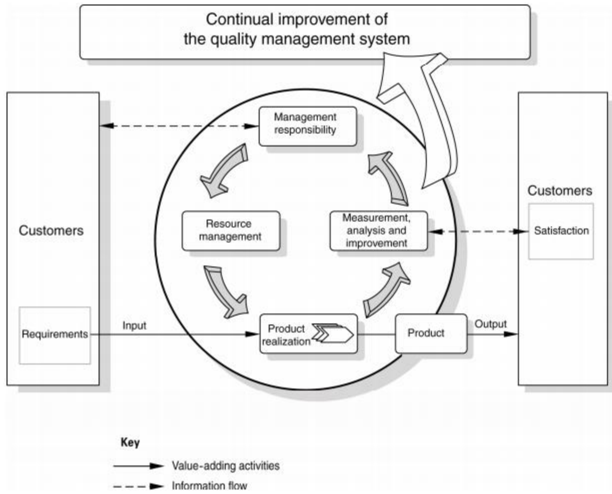


Figure 21- Continual improvement of the quality management system (ISO 2006).

7.1.3.2 AS ISO 10013:2003

AS ISO 10013:2003 relates to the Guidelines for quality management system documentation. The standard outlines that it is important to develop a sufficient amount of documentation to ensure the quality of effective planning, operations, control and continual improvement. Quality management system documentation can relate to the entire or a component of the system, these could relate to the nature of the product, processes, contractual requirements, governing organisations and the organisation. Outlines are given to assist with documenting of a quality management system. (Australia 2003)

7.1.4 **Maintenance**

The tunnel planners, road authorities, owners and other parties/organisations whom are involved with the O&M are responsible for the maintenance objectives specific to the tunnel. A typical objective for a road tunnel involves ensuring that both the system and equipment within the tunnel operate at and achieve the specified level of reliability and durability.

To achieve the specified maintenance objectives an asset management methodology must be specified. Three forms of maintenance are incorporated within tunnel maintenance. The firstly form is prevention maintenance which requires planned/routine maintenance activities. This could involve cleaning, calibrations, or replacing items that wear and tear. The second method consists of corrective maintenance which is the reactive form and results from equipment that is damaged or when failure occurs unexpectedly. Finally, major refurbishment and replacement involves major upgrades or replacement of structure, system or equipment. It is relatively infrequent and usually costly.

7.1.4.1 Maintenance manuals

Maintenance manuals should specify when action should be taken to complete maintenance duties on the tunnel while it is in operation. It should also include, but is not limited to:

- The intervention level at which maintenance should be carried out
- The service levels VS the defect
- Units of measurement for usability of asset elements
- Frequency of inspection
- Possible inspection level

Each specific area which the organisation is responsible for within the O&M will require a maintenance manual i.e. for the pavement.

7.2 TUNNEL EMERGENCY RESPONSE OPERATIONS

An emergency within a tunnel is any incident that may result in fatality, injury or damage to the structure. An Emergency within a tunnel may involve but is not limited to;

- Electricity
- Fire
- Steam pressure
- Traffic accidents
- vehicle breakdown
- crashes
- debris on carriageway
- spills
- lost loads
- over-height vehicles
- external electrical supply failure
- flood

When developing emergency response plans, particular attention should be given to human behaviour, facility ventilation and fire mitigation (Thompson & et.al 2011).

7.2.1 Ensuring Safety within Tunnels

To ensure safety within tunnels it is required to have sufficient;

- Communication between all stake holders
- Training of Emergency services and operator staff
- Incident management plans that are readily available to all relevant parties

It is important to note that tunnels are a constantly changing system. Throughout the lifetime of the structure, changes will be seen with characteristics associated with the tunnel (i.e. traffic flow) and hence constant review of the risks should be made. As an example traffic volume throughout the lifespan of the tunnel will change (often will increase). With significant flow of traffic through the structure, improvements need to be made to the systems that are monitoring and analysing. (Beard & Carvel 2005)

7.2.2 Prescriptive requirements

Design methods have been created over time through experience and historic events. When applying the prescriptive requirements the risks involved within the design are not fully understood. Upon commissioning of the tunnel the events that occur are better understood within the situation and hence may lead to better methods of tunnel design. (Beard & Cope 2007)

7.2.3 Assessing Risk

As noted previously, means of reducing risk can be done via implementation of codes or guidelines if available and relevant to the situation. A risk-based approach can be undertaken in conjunction with the codes/guidelines. A risk analysis should be conducted prior to tunnel design to ensure all major risks within the system are known and can be adequately designed for (AFAC 2001).

Conducting risk-based approach in analysing the risk of the tunnel poses issues with the best methodology of undertaking the assessment. With risk there are a number of categories of risk which differ based on the ability to pin point the underlying issue leading to an unsafe environment and the certainty of how to solve such a problem.

Firstly ‘hard’ methodologies pertain to situations where the underlying issue is known and a desirable methodology to reduce/eliminate the risk is also known. Methodologies range from ‘hard’ all the way through to ‘soft’ methodologies where, the underlying issue of the risk may not be well understood. Between these two methodologies is the intermediate methodologies which relate to situations where the underlying issue is understood however methodologies of eliminating/reducing the risk is unknown and hence a system of trial/error may have to be implemented. (Beard & Carvel 2005)

7.2.4 **Tunnel Fire Safety**

As noted earlier the ability to reduce risk is greatest within the planning and design phase of the project. Decisions around tunnel fire safety are generally based upon;

1. Fatality and injury
2. Property loss
3. Disruption of operations

Some basic issues surrounding fire risk within tunnels include, but are not limited to;

1. Fire risk results from the tunnel system as a whole involving design, operation, emergency response, and tunnel use. The system involves both design (traffic volume) and non-design (Individuals behaviour) elements
2. With increasing complexity (multi-modal/decked) and length of tunnels the risks need to be identified and dealt with effectively
3. The dynamic environment associated with tunnels. From the opening of the tunnel compared to a stage later within its lifetime the system will undoubtedly be different.
4. Defining what is acceptable in regards to fire risk
5. What is an appropriate methodology for fire safety
6. Life sized experimental tests
7. Replication is experimental test outcomes
8. Need to know more about tunnel fire dynamics
9. Fire suppression systems
10. Human Behaviour

It is know that tunnel fire science and engineering needs to be more widely understood. Research in the area of tunnel fires is very young and many questions remain unanswered surrounding the topic. Some areas of ambiguity that need to be researched into more widely include:

a) Effective ways of preventing fires occurring in tunnels
b) Factors effecting tunnel fire size and spread
c) Types of tunnel fire suppression systems
d) Human behaviour in relation to tunnel fire emergencies in relation to tunnel operators and emergency services
e) Evacuation systems
f) Automation of Emergency response
g) Uncertainty in models which are used as part of fire safety decision-making

7.2.5 **Fire mitigation**

Within Fire mitigation the following factors should be considered; spill control, traffic accidents, and tunnel length and lighting.

8 HISTORICAL REVIEW OF TUNNEL INCIDENTS

Although open road accident are more common than tunnel fires, accidents that occur within tunnels usually have a greater impact and can result in loss of life, infrastructure damage and can lead to greater social impacts. The reason for the greater damage incurred by tunnel accidents is due to the confined space, meaning that heat and smoke is trapped within the tunnel leading to structural damage and potential loss of life. Due to the nature of tunnels and their unfamiliarity to tunnel users, a tunnel fire can be a traumatic experience for all users involved.

A list of recorded tunnel fire incidents occurring before 2005 can be seen in Appendix 2. It should be noted that within

Appendix 2 the list will not provide a complete and accurate account of all fires that have occurred as many tunnels do no publish fires that occur, and information surrounding tunnel fires is difficult to obtain. It should be noted however that within the recorded historic events many of the high fatality fire events were caused due to HGV and rail. It was also seen that many of the Bus fires were able to be extinguished by the bus driver and the only event that lead to fatalities was due to human reaction, where it lead to loss of control by the driver. The effect of many incidences was increased by inadequate operations and system control.

Appendix 2 will be used as a guide only as the data is incomplete. Rail fires have caused less concern as it is thought that road tunnel fires are approximately 20 times more likely to occur. Within Europe it was found that only 3% rolling stock accidents involved fires. (Beard & Cope 2007)

With the need to increase the efficiency of transport networks, the emergence of tunnels has occurred. Safety within these tunnels is therefore vital in ensuring that the system remains efficient and the level of service through the tunnel remains high.

There is a (1:20) – (1:25) ratio on the likelihood of a rail tunnel fire occurring compared to a road tunnel fire (Peter 2010). The large number of fires that have occurred within tunnels has caused attention towards creating strategies to protect the tunnel users, structural integrity and operations (Hu, Huo & Chow 2008). Tunnel fires have played a devastating role in the past and have consequently led to extensive investigations into the protection and prevention of fires within tunnels. Improvements have been made to modelling fire and hence is allowing for increasingly more accurate predictions of fire risks within tunnels.

8.1 ROAD TUNNELS

The most common means of fatalities within tunnels has been found to occur due to general traffic accidents (refer to Table 9). From Norwegian data an approximation has been made that two thirds of the tunnel incidents are related to traffic accidents and the remaining one third was due to tunnel fire or dangerous goods accidents. Table 9 below provides a summary of the potential loss of life for road tunnel incidents in Oslo.

Table 9 - Tunnel incident life loss in Oslo (Beard & Cope 2007)

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

Although the cause of fatalities within tunnels is dominantly common traffic accidents, fire related incidents usually have multiple deaths and hence cause concern. When a fire occurs within tunnels, they tend to trap both smoke and heat which can become fatal for tunnel users.

8.1.1 Statistics of tunnel fires

Beard and Cope, 2007 conducted an study upon international tunnel fires, from 1987 to 2006. Forty-nine incidents were recorded within this time involving tunnel fires (refer to Figure 22). It should be noted within the following diagrams that HGV stands for 'Heavy Goods Vehicle' (Beard & Cope 2007).

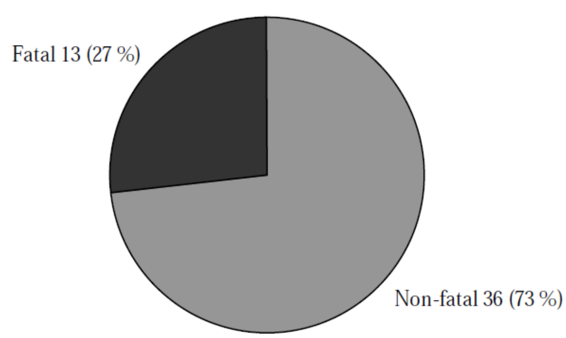


Figure 22- Significant fires world-wide (1987 - 2006)- not including during construction or terrorism (Beard & Cope 2007)

Tunnel fires have involved a number of different vehicles (refer to Figure 23) including busses, HGV, trucks and tankers. It is shown in Figure 23 that tankers carrying 'dangerous goods' (such as petroleum) are not the only cause of tunnel fires. A majority of the fires are made by HGV (61%) and busses (31%). The reason for the higher fatalities is the correlation between fire loading and heat release rate (refer to chapter 4.2).

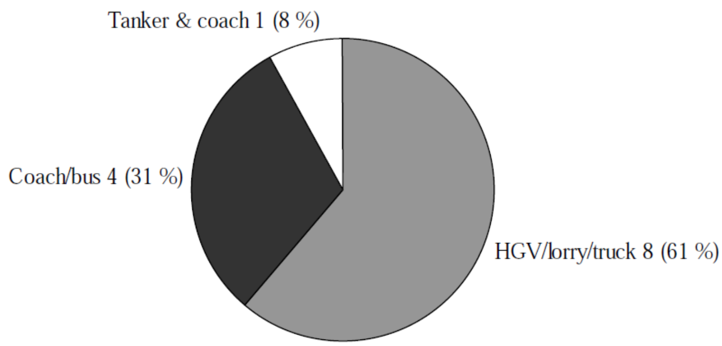


Figure 23 - Fatalities in international tunnel fires from 1987-2006 (specific vehicle types)

8.1.2 **Findings**

It was suggested by Beard and Cope, 2007, that although there have been improvements to the information and control system within a tunnel to detect and respond to an incident, there are still increasing numbers of road accidents. This could be said to be a result of a number of reasons;

a) Increasing traffic volume
b) Increasing transportation of Hazardous goods
c) Increase kinetic energy due to higher traffic speeds (particularly true on rail)
d) Increasing length of road tunnels – this has been a trend to reduce Environmental impact
e) Growing risk of terrorism – in Germany 50% of fires have been thought to have been started deliberately (Beard & Cope 2007)

STUVA had carried out major Fire testing which was validated in Norway and is still valid today;

a) The flashover (simultaneous ignition of combustible material in close proximity within an enclosed area) point will occur within 7-10 minutes of the initial fire beginning
b) Depending on external conditions the fire duration within the vehicle is subject to alternate external conditions and hence could last 30minutes up to a number of hours
c) Smoke inhalation is a considerable concern due to the high quantities of gas that even small fires can cause
d) In some tunnels visibility was an issue due to the cross section filling with smoke quickly after a short period of time
e) Ceasing fires within tunnels is difficult due to access restrictions and extreme heat radiation

f) High fire load has been seen to cause extensive damage to the structure.

Within tunnels, railway and motorway vehicles cause a fire load of approximately 60-80kg per square meter compared to residential building containing a fire load of approximate 30-60kgper square meter. This increase in loading is another explanation for increased severity of tunnel fires.

8.1.3 Case study - Mont Blanc tunnel fire

The Mont Blanc tunnel fire occurred on the 24th of March 1999. The fire was initiated by a truck with a thermal foam trailer containing flour and margarine. There were 38 fatalities and the Fire Chief was sent to hospital along with two victims found in a refuge. (AFAC 2001)

Table 10 - Mont Blanc tunnel characteristics (AFAC 2001)

Characteristic	
Length	11.6km
Traffic	Bi-directional
Vehicle rests	Located ever 300m
Safe refuge area	At every second rest area
Extinguisher	Every 100m
Call Point	Every 100m
Fire Brigade personnel hydrants, telephones and call points	Every 150m

This study was chosen to highlight the learnings that came from the event. The learnings from the fire consisted of:

1. The speed and magnitude of the fire that developed within the truck led to the spread of fire to other vehicles
2. Smoke extraction through the ventilation system was limited by capacity
3. The fire was accelerated due to the a higher supply of air than exhaust
4. Inadequate equipment (lights, ventilation, no central facility, lack of fire water, fresh air ducts to refuge)

The learnings highlight the importance of the fire load along with the physical system that the fire interacts with.

8.2 RAIL TUNNELS

Incidents within rail tunnels had not been clearly documented and hence results in a gap of information. However, the greatest rail tunnel incident was believed to be the Armi tunnel in 1944, Italy which resulted in 450 fatalities due to carbon monoxide inhalation. As mentioned earlier, within Europe studies suggest that rolling stock fire incidents constitute approximately 3% of all incidents in rail (Beard & Cope 2007).

8.2.1 **Statistics of Rail fires**

Rail network fire fatality rates, were estimated using data for several countries including Scandinavia, UK and France. The indicative results estimated that approximately 0.25 deaths per billion persons per km (Beard & Cope 2007).

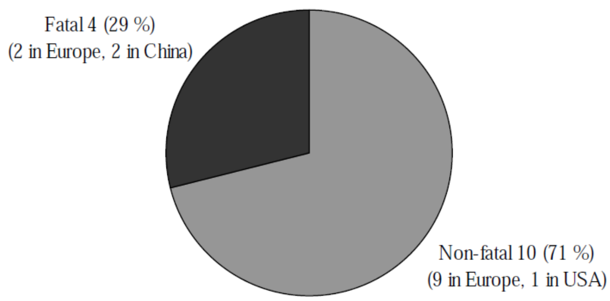


Figure 24 - Rail tunnel fires world-wide (1987-2006)- (Beard & Cope 2007)

Figure 24 above shows that there have been approximately 14 major rail fires worldwide with 29% of those pertaining to mortality. Although there has only been 4 fatal rail tunnel fires the death rate associated with these fire is significant. Figure 24 show the four fatal railway tunnel fires involve a total of 254 deaths. Of these 254 deaths, 155 deaths were associated the Kaprun train located in Austria.

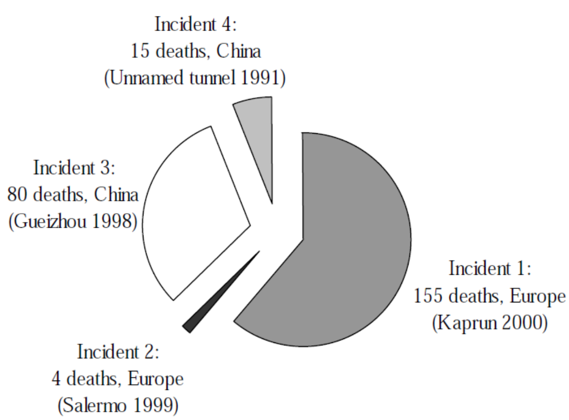


Figure 25 - Rail tunnel death rate/ locations (1987-2006) (Beard & Cope 2007)

8.2.2 **Case study - Kaprun Tunnel, Austria, 2000**

The Kaprun tunnel in Austria is used to pull skiers up and down a mountain to the Kaprun Glacier. The tunnel has a 45 degree angle and is 3.2km long. A sketch of the tunnel can be seen in Figure 26.

On the 12th of November 2000, a train being pulled to the top of the glacier came to a stop 600m into the tunnel. The train turned into a raging inferno where the steep tunnel acted as a chimney sucking the smoke up. The fire began in the final cabin where people tried to break windows to escape; meanwhile the train drive did not know what was happening. As the driver didn't know of the incidence, emergency evacuation couldn't be carried out effectively and hence lead to poor communication to the operation centre along with emergency services. There was 155 death and 12 survivors for the event. The disaster was thought to be caused be an ill designed heater with pressurised hydraulic oil dripping onto the heater element and resulting in flames.

The lack of safety within the train was encouraged by the will to be competitive with other ski resorts. The faulty design and safety cut backs were the main cause of the fire and show the important of ensuring safety measures are implemented (BBC 2004).

This case study was chosen to highlight the importance of sufficient maintenance and the importance of communication. The lack of ability of the rail users to communicate with the driver resulted in elongated time for realisation which reduced the ability for all users to effectively escape and increased the time for emergency services to extinguish the fire.

The study also highlights the natural ventilation system which was a great example of the chimney effect. The smoke egressed from the top of the tunnel and hence the passengers tried to escape in the opposite direction.

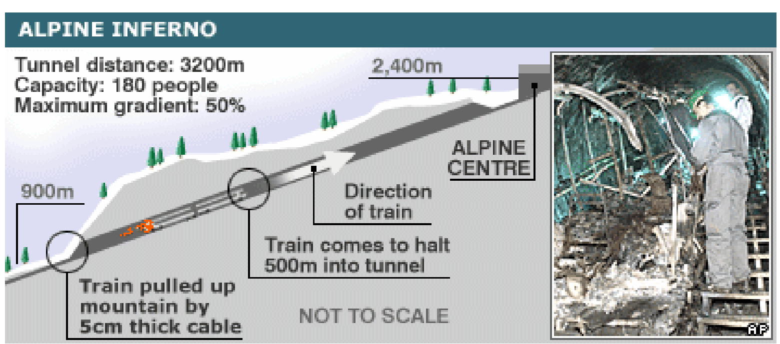


Figure 26 - Kaprun tunnel fire (BBC 2004)

8.3 VEHICLE FIRES

Vehicle fires have a number of causes for the ignition of fires. These causes comprise of worn components, poor workmanship, age or normal deterioration and unsufficient maintenance.

Buses and coaches fires cause much concern as they carry a large number of people (more than 22 people) - (Hammarström, Axelsson & Reinicke 2004). The Norwegian and Swedish road authorities conducted an investigation into the cause of bus fires. It was found that around 1% of busses caught fire per year. There will be variations within the Australian and the Nordic countries bus fire statistics due to the variation in the climate, maintenance plans and bus designs and hence the statistics will vary across countries. For the purpose of this study the Norwegian and Swedish data will be used as it is readily available and sufficiently documented which is not the case for Queensland. For completeness of data and for better insight into the occurrence of bus fires a study should be undertaken within the Brisbane area to demonstrate the impact it will have upon the Busway and how these occurrences can be reduced.

Table 11 and Table 12 show the fires that have occurred within bus/coaches within Norway and Sweden. The causes for many of the fires have been noted to ignite due to the following categories:

1. Technical fault
2. Arson
3. Unknown

Table 11- Norwegian bus/coach fires between 2000-2004 (Hammarström, Axelsson & Reinicke 2004)

Year	Number of buses/coaches	Number of reported fires	Number of reported fires, (%)	Total no. of fires, including uncertainties	Total number of fires, (%)
2000	8 608	34	0,40	57	0,66
2001	8 542	57	0,67	95	1,11
2002	8 518	57	0,70	95	1,12
2003	8 494	52	0,61	87	1,02
2004	8 520	45	0,53	75	0,88
Mean value	**8 519**	**49,0 (5 years)**	**0,58**	**81,8 (5 years)**	**0,96**

Table 12 - Swedish bus/coach fires between 2000-2004 (Hammarström, Axelsson & Reinicke 2004)

Year	Number of buses/coaches	Number of reported fires	Number of reported fires, (%)	Total no. of fires, including uncertainties	Total number of fires, (%)
1996	14 720	68	0,46	114	0,78
1997	14 783	65	0,44	109	0,74
1998	14 902	64	0,43	107	0,72
1999	15 106	83	0,55	139	0,92
2000	14 536	105	0,72	175	1,20
2001	14 465	121	1,45	202	1,40
2002	14 292	123	0,86	205	1,43
2003	14 120	139	0,98	232	1,64
2004	13 883	125	0,90	209	1,51
Mean value	**14 464**	**122,6 (5 years)**	**0,85**	**204,6 (5 years)**	**1,42**

The causes for the fires in Norway were broken down into the causes of the fires. The technical faults were further broken down into four categories; electrical, leakage, unspecified and friction (wheel system or breaking system). The results can be seen below in Figure 27.

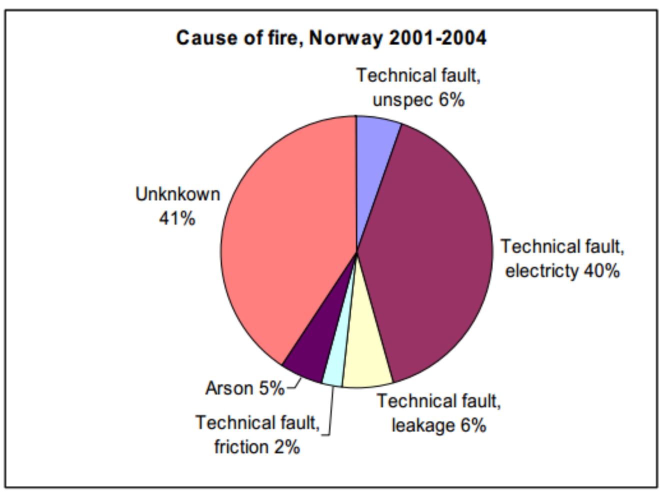


Figure 27 - Causes of bus fires between2001-2004 in Norway (Hammarström, Axelsson & Reinicke 2004)

8.4 SYDNEY HARBOUR TUNNEL CASE STUDY

The Sydney harbour tunnel case study was chosen to be discussed within this study as it highlights the human behavioural system and how people respond to certain aspects of an emergency response system. This study will be used as a guide for human behaviour.

A study was undertaken in the Sydney Harbour Tunnel to observe the behaviour of 32 volunteer (aged 16-81) tunnel users during a controlled fire (burning car) evacuation process. It was noted that there was a lot of confusion surrounding the fire incident and the major factor contributing to the success of the evacuation was the pre-recorded audio messages played via the radio and over the PA (public announcement) system.

The study highlighted that 94% of the participants based their action on those of others. A group of young males was the first to exit their car. It was noted by one participant that; *"[I] opened the door when I saw the sign above then saw others still in cars so got back in and shut the door". (Burns et al. 2013)*

There were a list of reasons reported pertaining to why the volunteers preferred to follow the actions of others including; reassurance, believing others were more knowledgeable and uncertainty about how to respond to the situation. It was also noted by the volunteers that in a real scenario they would have checked the burning car for occupants. (Burns et al. 2013)

Another concern that was noted by the participants of the Sydney Harbour Tunnel fire was that they were leaving private property in an unfamiliar environment. Hence there was ambiguity around leaving their vehicle and keys behind and how they would retrieve their cars. There was also a belief that one is safer when in close proximity to their car.

A more detailed list of events during the case study was documented and can be seen below in Table 13.

Table 13 - Response times from all cars coming to a halt (Burns et al. 2013)

Response phase	Mins: secs	Events
Initial inertia phase	0:00	All cars come to an initial stop behind the lead vehicle ~100 metres from the burning cars. Ceiling signs are visible: "turn off engine" and "turn on radio."
	0:16	First movement from participants outside car: several heads protruding from open car window.
	0:53 - 0:57	First car door opens, then closes when tones of first PA message start.
Audio instructions to wait in car followed	0:55 – 1:15	PA speaker starts first announcement asking people to stay in their cars and await further instruction (Figure 1 paragraph 1).
	1:25	The last car finally stops manoeuvring.
Evacuation phase	2:12	Announcement says "you are now required to evacuate the tunnel."
	2:12	First person, young male, exits car and is followed steadily by all other participants. There is no sense of urgency.
	4:04	All participants have left the incident tunnel.
Safety reached 2 mins 5 secs	4:19	Last person exits the cross tunnel into the non incident southbound tunnel.
Evacuation continues in non-incident tunnel		In southbound tunnel evacuees follow audio instructions.

9 ØRESUNDSBRUN

For emergency response to be efficient it is required to have clear communication between all stake holders, training of emergency services and operator staff and incident management plans that are readily available to all relevant parties. To ensure all of objectives are met and emergency response can be carried out quickly and efficiently it is important to have sound working relationships between stakeholders and clearly defined roles.

The structural design of the BaT tunnel is not a new concept as there is decked tunnels currently operating within the world today (refer to Table 14). The concept of incorporating multiple modes within a tunnel has also been incorporated within tunnels (refer to Table 14). However incorporating a decked, multimodal tunnel which links to underground stations over a length of 5.4km where public transport is the only users is a new concept for Queensland and within the world, hence it is important to draw on past experiences and utilise knowledge and apply it to the BaT tunnel.

One major aspect that will contribute to the success of the BaT tunnel is the operation and management of the tunnel. As discussed within Chapter 7.2 there is a relationship between operation and maintenance and the success of the Emergency response system. It is therefore important to define roles, create relationships and ensure clear communication between stake holders. In the past there has been no need to form relationships between Queensland Rail and Brisbane Transport as public transport modal change within SEQ has been limited or facilitated by Translink.

Within the BaT tunnel both rail and bus consortiums will need to work together to ensure the integrity of the structure, safety of all users and ease of modal changes. The Øresundsbrun is a well-documented example of sound management and how two countries can work together to maintain efficient operations. The Øresundsbrun connects Copenhagen with the southern Sweden city of Malmö and hence there is communication between both countries that in the past would not have collaborated together. The Øresundsbrun has a lot of information readily available about the management of the bridge. It was therefore chosen to investigate the Øresundsbrun's management hierarchy, communication systems and relationships between the states during the event of an emergency.

Table 14 - World decked tunnels

Tunnel	Decked	Mode/s	Country/City
BaT	Yes	Bus and Rail	Australia –Brisbane
Øresund	No	Rail and traffic	Denmark & Sweden
Alaskan Way	Yes	Motorway	USA - Seattle
SMART	Yes	Motorway and flood mitigation	Malaysia – Kuala Lumpa
Orlovski	Yes	Road	Russia
Al Variante di Valico	No - Parallel	Parallel Motorway	Italy
Chongming	Yes	Traffic and light rail	China
Fehmarnbelt	No	Rail and traffic	Denmark & Germany
A86	Yes	Motorway	Paris
Fuxing Road Tunnel under the Huangpu River	Yes	Motorway	China

9.1 BACKGROUND

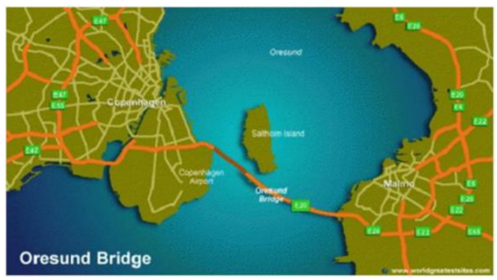


Figure 28 - Oresund Bridge

The Oresund Bridge connects Copenhagen with the southern Sweden city of Malmö (see Figure 28 - Oresund Bridge). The structure consists of a bridge, an artificial island and a tunnel. Øresundsbro Konsortiet is jointly owned by the Danish and Swedish states where A/S Oresund and Svensk-Danska Broforbindelsen (SVEDAB AB), both own and operate sections of the Oresund Bridge on their respective sides. The agreement between the two companies is outlined in a consortium agreement that is approved by both governments. (Konsortiet 2005)

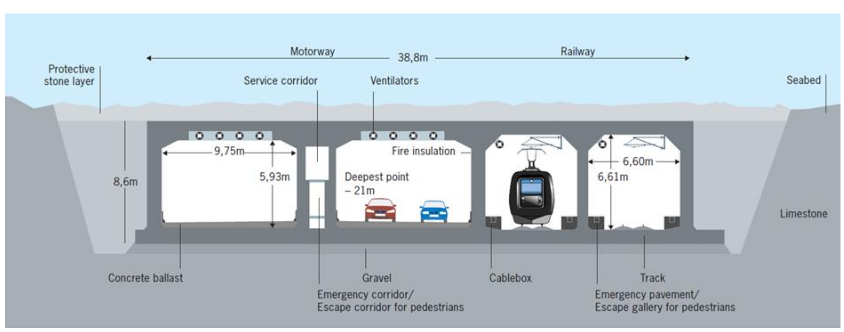


Figure 29 - Cross sectional view

9.2 Management Overview

A/S Øresund owns and operates the Øresund motorway. They also own the Øresund rail however the operation and maintenance is carried out by Banedanmark (Danish National Railways Agency). Banedanmark then pays A/S Øresund a fee for the use of the infrastructure. A/S Øresund owns half of the Øresundsbro Konsortiet where Øresundsbro Konsortiet looks after A/S Øresund finances. Staff receive contracts through Øresund however they are hired through Sund & Bælt. (Sund&Bælt 2014)

Sund & Bælt Holdings A/S is responsible for the administration of six subsidiaries. It also acts as the operator for A/S Øresund and A/S Storebælt where it also holds administrative responsibilities. The responsibility of Sund and Bælt in relation to the Øresund Bridge involves:

1. Maintenance of the Øresund motorway
2. Ensuring the collection of fees from Banedanmark (Rail Net Denmark) for user rights to the Øresund line on Amager (The Danish Island)
3. Overseeing the part ownership of Øresundsbro Konsortiet
4. Managing the repayment of A/S Storebælt's and A/S Øresund's debt portfolios

A/S Storebælt is the owner of the Storebælt link along with the road and rail joint to it. A/S Storebælt ensures the operation and maintenance of the road link and the maintenance of the rail link is maintained at an acceptable standard.

SVEDAB AB is owned by the Swedish government and owns half of the Øresundsbro Konsortiet. Both A/S Øresund and SVEDAB AB are responsible for the land care on their respective side of the Øresund which is outlined within the consortium agreement. (Konsortiet 2005)

An overview of the management structure is given below in Figure 30.

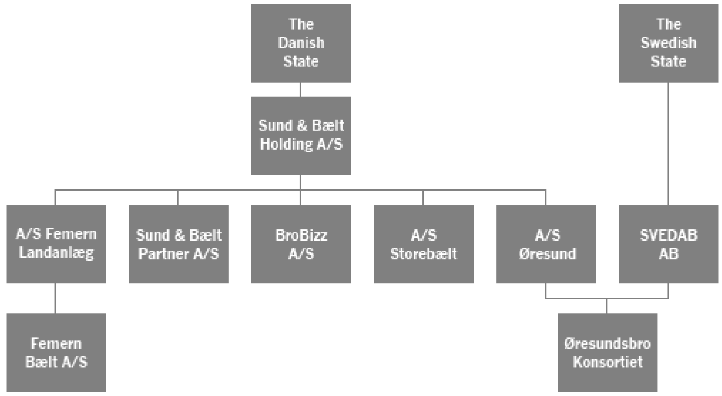


Figure 30 - Management structure

From this general overview of the management structure it is seen that a lot of planning has gone into defining the roles and ensuring that both the Danish state and Swedish state have joint responsibilities for ensuring the integrity of the structure. Both parties jointly own an external consortium and outline their responsibilities within the consortium agreement.

The BaT tunnel should involve an agreement between both the all stake holders which clearly outlines the responsibilities of both parties and ensures that in the event of an emergency, sound working relationships are established. The BaT tunnel is not working between two states or competitors however responsibilities are still required to be established.

10 IMPORTANT FINDINGS

10.1 LITERATURE REVIEW

Within the literature review there is a number of key factors that will be extracted and summarised for the use within the analysis. Table 15 highlights these elements.

Table 15 - Important findings within the Literature review

Chapter	Findings
Fire	• Fire involves O^2, heat and fuel • Tunnel fires are critical as they are confined spaces and hence temperatures can reach temperature of 1200 degrees Celsius within a few minutes • Fires can be classified based on time/temperature curves • Rail and Bus tunnels must use the RABT-ZTV (rail) time/temperature curve based on AS 4825 – 2011 • Tunnel fires can be ventilation controlled or fuel controlled
Tunnel Fire Risk	• Prevention and protection methods to reduce risk • A big risk is the vehicles traveling within the tunnels • Fire safety is a result of tunnel design, tunnel management and emergency response
Tunnel fire safety components	• All tunnels are different. All tunnels are dynamic in nature. • Economics plays a major role in justifying the level of safety a tunnel will adopt • Some major components that contribute to safety within a tunnel consists of; the ventilation system, human behaviour, fire mitigation, egress times and information and control systems
Operation and Maintenance of road tunnels	• There are many similarities between the operation and maintenance that takes place within road tunnels and the BaT tunnel • Operations includes; normal operations, incident management by altered operating conditions and incident response by tunnel closure • Procedures must allow for feedback to continue to improve the system • Emergency response must ensure; communication between all stake holders, training of Emergency services and operation staff and incident management plans that are readily available to all

Tunnel fire science is a young area where more research needs to be conducted into the following areas:

a) Effective ways of preventing fires occurring in tunnels
b) Factors effecting tunnel fire size and spread
c) Types of tunnel fire suppression systems
d) Human behaviour in relation to tunnel fire emergencies in relation to tunnel operators and emergency services
e) Evacuation systems
f) Automation of Emergency response
g) Uncertainty in models which are used as part of fire safety decision-making

10.2 HISTORICAL REVIEW OF TUNNEL INCIDENTS

Within the data gathering process a number of key findings were extracted and listed within Table 16 below.

Table 16 - Important findings from the historical review of tunnel incidents

Case / topic	Findings
Road tunnels	• The higher the fire load the more serious the fire, the typical types of vehicles involved with tunnel fires are HGV, Buses and lorries • The speed and magnitude of a fire can led to the spread of fire to other vehicles • Fire can be accelerated due to a higher supply of air than exhaust • Inadequate equipment can lead to fires (lights, ventilation, no central facility, lack of fire water, fresh air ducts to refuge)
Rail tunnels	• Rail fires occur less but are generally more catastrophic than road tunnel fires • Communication is a major component involved with the effectiveness in an Emergency Response plan • The ventilation system and the effectiveness of smoke control plays a major role in the direction of egress and the ability for emergency services to ingress
Vehicle Fires	• Major causes of bus fires includes; worn components, poor workmanship, age or normal deterioration and unsufficient maintenance • There is a correlation between the grade of a tunnel and the number of fires that occur (increased use of breaking leads to increased number of fires)
Sydney Harbour Tunnel	• 94% of the participants based their action on those of others • It was also noted by the volunteers that in a real scenario they would have checked the burning car for occupants. • People are uncomfortable leaving private property in an unfamiliar environment • Clear instructions and use of the PA system was a major component of the success of the system.
Øresundsbrun	• Sound operations depend upon sound relationships and the definition of roles • Øresundsbrun is a good example of how management of a single asset can be managed between two countries • An external consortium was established to maintain the cooperation between the two states.

11 Analysis

Two scenarios will be analysed using the Root Cause Analysis (RCA) framework which is a method that is outlined in Chapter 3 of the study. The RCA will be applied to the BaT design and the causes of fatality in relation to the tunnels non-design elements (human behaviour). To undertake the analysis first a definition of the scenarios must be made. Publically available information will be used to define the layout of the tunnel and practical assumptions will be made in the case that insufficient information is available for the design. The outcome of the root cause analysis is hoped to outline the potential causes of fatality in the event of a tunnel fire due to non-design elements.

There are two areas of tunnel fire safety, prevention and protection. Prevention is known to be measures relating to preventing an event occurring, where protection is measures relating to reducing the impact when an incident does occur. Within this analysis recommendations will be generated in relation to tunnel fire risk protection, hence the fire is assumed to have already begun and the analysis will be conducted into the reactions that follows this event.

11.1 Defining the Problem

Many fire scenarios could occur depending upon the parameters of the fire, characteristics of the staff and the tunnel users, layout of the tunnel, ventilation system and the procedures that need to be followed. Due to the large number of input parameters the root cause analysis is a good approach to looking at the problem however there are limitations to the method which will be discussed within chapter 12.2. The Root Cause analysis methodology is able to analyse a series of events and look at all possible scenarios, extract common root causes to the problem and finally produce appropriate recommendations to decrease the risks involved with tunnel fire human behaviour. Hence within this analysis the definition of the following parameters will be defined:

- Tunnel layout
- Tunnel management
- Emergency response

11.1.1 Assumptions

The BaT tunnel is a complex system that incorporates both human and functional systems. The focus throughout the study will mainly be upon the human system which incorporates both human and non-human aspects. The human aspects involve human behaviour and the components of the system that the humans interact with. The functional system incorporates all components of the system that have a specific function (such as the ventilation system). The analysis will be conducted into the failure mechanisms associated with the human system and hence further simplifications and assumptions will be made about the non-human aspects of the tunnel.

The BaT tunnel tube will be assumed to be uniform in cross section (as seen in Figure 31) where the longest section between the underground stations will be analysed with a grade that is assumed to be dictated by the new generation of rolling stock. The analysis of human behaviour will be undertaken within two defined scenarios. It will be assumed that the fire has already ignited and the analysis will be done upon the behaviour of the tunnel users in reaction to the fire and the risks that is imposed by their behaviour which could lead to the potential loss of life.

To simplify the problem, the tunnel will be broken into compartments where the busway, railway and stations are to be analysed as individual entities. The busway and railway are structurally separated and only in the case of structural failure would there be carry over effects into the alternate modes way. When the fire reaches the stations the smoke and heat is assumed to exit through the ventilation outlets ducts. This was assumed to simplify the modelling and as the functional system is assumed to be sound, the only uncontrollable variable is the human system.

The human behavioural components of the busway and railway have minimal impact upon each other in the event of a fire as they are structurally isolated. Interaction between the modes and public transport users will happen within the stations. The focus of this dissertation is upon tunnel fire safety and hence the interaction that occurs within the station is outside the scope of this dissertation. However, it is not practical to assume that within reality the entire system operates in isolation as the effects of smoke, heat and human interaction would be translated longitudinally through the structure and into the stations. Heat would be transferred throughout the structure and within the design process assessment should be undertaken into how much heat will transfer between the decks and the effects it will have upon the alternate mode during operations. However, for the purpose of assessing the non-design system following the event of a fire, the busway and railway will be viewed in isolation and hence, it will be analysed separately.

Within this study the tunnel will only be analysed during incident management altered operation conditions and will not consider periods of construction and downtime.

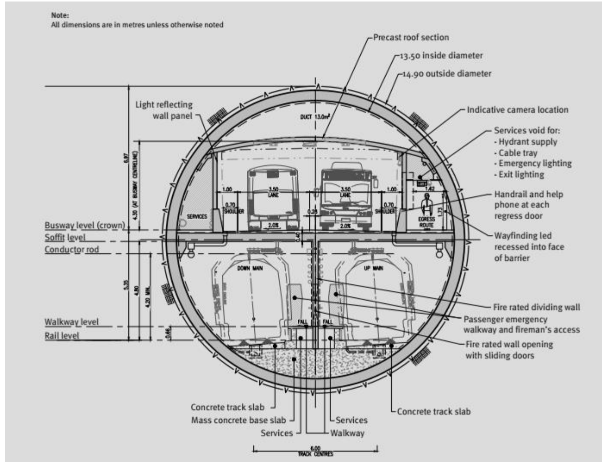


Figure 31 - BaT tunnel conceptual design cross section

11.1.2 **Design Fire**

The busway can be viewed in isolation of the railway tunnel and underground station for the purpose of this dissertation. The busway fire poses interesting issues as it has not been analysed within previous studies. It is assumed that the fire within the busway occurs upon a bus within the engine. The emergency egress exits are 120m apart.

The Railway fire is assumed to emerge within a coach of the new generation of rolling stock. It is assumed that evacuation can take place into the alternate railway tube every 250m where they can make safe journey to the nearest exit.

The parameters for both the busway and railway fire will be assumed to be identical in accordance with AS4825-2011. It is assumed that the bus and rail fires will have similar fire loads. Hence the variations between the scenarios will be involved with the tunnel design, tunnel management and emergency response.

An extreme fire event will be assumed to follow the RABT-ZTV (train) fire time/temperature curve and hence will reach temperatures of approximately 1200 degrees Celsius within 5 minutes of ignition (see Figure 32).

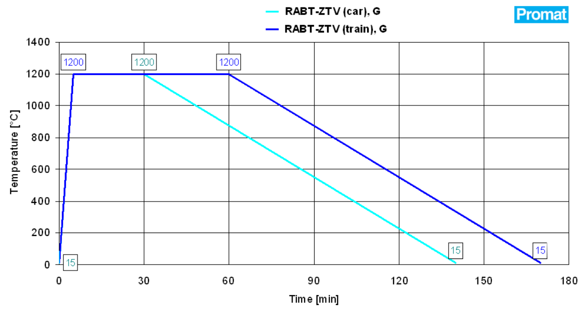


Figure 32 - RABT-ZTV (rail) time/temperature curve

11.1.3 **Emergency response procedure**

In the event of an emergency all stake holders will be informed following the recognition of the fire by the operations team. The stakeholders will include the tunnel staff, Public transport staff, Tunnel owners and operators, Emergency response team and the Emergency services.

The purpose of emergency response will be:

- Maximise the safety within the tunnel
- Minimise the time taken to clear incidence
- Minimise time for emergency services to appear onsite
- Minimise the risk to emergency services
- Minimise the time taken to extinguish the fire
- Minimise potential loss of life

The emergency response will be incorporated into the information and control (SCADA) system and will include;

1. Lighting
2. Ventilation system
3. CCTV
4. Fire detection system
5. Fire deluge system
6. Tele control
7. Public announcement system
8. Incident detection system
9. Communications systems
10. Traffic control systems
11. Radio and Wireless

Upon design of the tunnel, all stake holders are assumed to have developed the emergency response plan. They are assumed to have ran a series of scenarios to train the staff and how they respond to the scenario. All personal that take part within the emergency response will have defined roles and have sufficient training to deal with many situations.

11.1.4 **Tunnel Users**

The maximum number of passengers on the busway travelling from the south of Brisbane to the CBD will increase significantly. Capacity will increase from approximately 10,400 to 23,100 per hour (DTMR 2013). The capacity for commuters getting to the CBD from the north will increase from 5,200 to approximately 17,900 per hour. The BaT tunnel will ease the bus congestion on the Captain Cook Bridge and allow more access for private vehicles. (DTMR 2013)

11.1.5 **Tunnel layout**

The tunnel section that is being investigated will be assumed to be between fire isolated exits. There will be a 240m (120m either side of the exit as per AS4825-2011) section for a bus and 500m (500m either side of the exit as per AS4825-2011) for the railway. Within the busway it is assumed that there will be 16 buses that have to egress through a single exit. The busway will consist of the road, services compartment, and a duct ventilation compartment along the crown of the tunnel (Figure 31). The railway will be bidirectional which will be separated via a fireproofed wall to prevent the effects of Bernoulli (Figure 31). The ventilation system will incorporate jet fans at the stations and will suck the smoke towards the stations.

Figure 33 - Busway (left) and railway (right)

11.2 BUSWAY

The busway will be viewed in isolation from the railway. The analysis will be done upon the human behaviour that occurs following the ignition of a fire within the tunnel (specifications of the fire will be described below). The assumptions made within Chapter 11.2 will be made using the standard practices for road tunnel operation and maintenance guidelines (as seen in chapter 7). The assumptions will also be made in relation to the BaT tunnel preliminary design characteristics seen in chapter 2.3.

11.2.1 **Busway layout**

The tunnel will have bidirectional flow without a division barrier. There is a ventilation duct along the crown of the roof ($13m^2$). In accordance with AS 4825-2011 there will be 120m between tunnel exits. See Figure 33 above.

11.2.2 **Bus fleet specifications and Busway capacity:**

The only vehicles entering the upper deck of the tunnel will be busses. The busses are all assumed to be Volvo B10L.

Figure 34- Volvo B10L

The Volvo B10L has the following characteristics:

- Capacity: 62
- Dimensions (m): 12 x 2.48 x 3.3
- Loaded weight: 20 tonnes

Within accordance of AS 4825-2011 the tunnel should be designed for degraded operations during the worst peak hour scenario (to be conservative degraded operations can be considered to be one missed headway for degraded operations). To allow for the root cause analysis it will be assumed that there will be 16 buses that need to be evacuated through a single fire exit.

11.2.3 **Busway operations**

In accordance with AS 4825-200 the tunnel will be designed for commuters where the buses are driven by staff with training in emergency response.

The operational times is assumed to be identical to the Brisbane Transport operational times:

- Monday – Friday 5.00 am – 12.30 am; and
- Saturday – Sunday 12.00 am – 12.00 am

The busway operations and maintenance will be responsible for:

- Communication between all stake holders

- Training of Emergency services and operator staff
- Incident management plans that are readily available to all relevant parties

The emergency response fixed installation will include:

- Automated detection system
- Door monitoring
- Warning signs
- Pre - recorded PA system
- Live directed
- Radio rebroadcast
- Variable message
- Continuous monitoring
- Incident detection
- Emergency phones
- Emergency service radios
- Traffic flow detection
- Variable message signs
- Lane use signs
- Radio broadcasting
- Control room
- High reliability control system
- Fire Isolated exits
- Fire separation of power source
- Fire protection of electrical circuits

The equipment found within the Bus will include:

- First Aid Kit
- Fire Extinguisher
- Two Way Radio
- Emergency Parking Brake
- Safety Latch on the Emergency Exits

11.2.4 **Bus driver training**

Bus drivers will be trained and familiar with:

- Rear Door Evacuation

- Side Door Evacuation
- Split Door Evacuation
- For a Bus Rolled over

11.2.5 Busway egress path

The busway egress path is critical for determining the egress time that could be encountered during evacuation. Within the tunnel design passengers must exit though fire isolated exits, once in these exits the passengers can egress through the underground stations on the surface.

Egress time from the busway is made up of realisation, bus evacuation, queue time and tunnel evacuation.

11.3 RAILWAY

The railway will be viewed in isolation from the busway. Railway fires have occurred throughout history where a list of rail fires can be seen within

Appendix 2. The main cause of tunnel fires is electrical faults, arcing and friction. This tunnel fire will be assumed to begin within a coach.

11.3.1 Railway Layout

The railway allows for bidirectional flow and is separated by a fire proof wall. There is a walkway that allows for passengers to egress from the train without the need to change levels i.e. a ladder.

Within the tunnel the following parameters will hold true:

- Longitudinal ventilation: Jet fans located at the portals and underground stations
- Door monitoring systems
- Mobile phone coverage is available
- Driver radio communication
- On-board PA
- Tunnel emergency phones
- Traffic flow detection
- Control Room
- On site incident control room
- Walkway
- Illuminated exit signs for way finding
- Portable extinguished
- Spalling protection
- Redundant water supply
- Booster facility
- Internal hydrants (ring main)
- Hydrants at portals
- Fire protection of power sources and electrical circuits
- Integrity of anchors and fixings
- Dual power supply
- 240m between tunnel emergency exits

11.3.2 Headway

Rail has requirements for sufficient headway to stop and prevent a collision. The headways are kept via the use of sop signals. Refer to Figure 35 for a proposed layout of the headway system. The higher the headway between the rolling stock the lower the risk imposed within a tunnel fire event and higher the ability to egress.

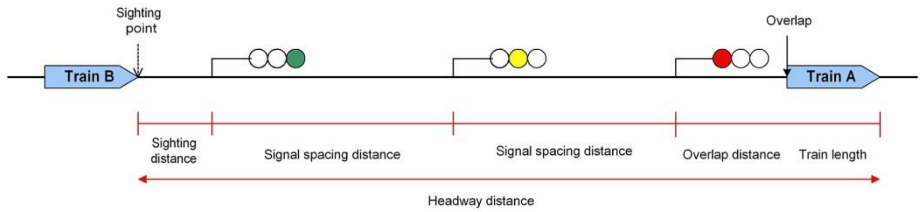


Figure 35 - Rail headway

11.3.3 **New generation of rolling stock**

The new generation of will be six-car trains where an artist's impression of the train can be seen in Figure 36. The BaT tunnel will be designed for use by the NGR.

Figure 36 – NGR (DTMR 2013)

The operating hours of the railway will be the same as that of the busway:

- Monday – Friday 5.00 am – 12.30 am; and
- Saturday – Sunday 12.00 am – 12.00 am

11.3.4 **Egress path**

When egressing from the train there will be a pathway that the commuters can use. There will be 250m between fire isolated doors. These doors will open into the alternate rail section where the passengers can then egress along the length of the tunnel into the stations and out onto the ground surface.

11.4 BUSWAY ROOT CAUSE ANALYSIS

Casual factor charting is a process of listing the sequence of events and creating a skeleton chart to display the results that could lead up to a failure. The process used to identify causes of fatality will be the Root Cause analysis which is described in section 3.1. This will be applied to the fire scenario described in chapter 11.2 in relation to the human system within the busway and how the sequence of events could occur from the moment of fire ignition through to fatality. Following the casual factor charting, the casual factors will be extracted. Casual factors are defined as events that if removed it would lead to a reduced event or would eliminate the entire event. Following the identification of the casual factors the root causes of these will be found using a flow chart and finally recommendations will be given and displayed in a table format.

To simplify the ability to carry out the casual factor charting process the fire has been sectioned into two distinct phases; Recognition and Response. The recognition phase will describe the events occurring between ignition and the beginning of lead up to the response plan. The response phase will highlight the sequence of events that take place after the emergency services have been notified and the emergency response team begin responding to the problem. Following the casual factor charting the casual factors will be extracted and explained.

The casual factor charting was undertaken for the busway and is displayed in Appendix 3. The casual factor charting process begins with a fire occurring in the busway; the potential reactions following the fire ignition will be documented and explained.

Following the ignition of a fire within the Bus and Train tunnel it is assumed that busses will continue to enter the tunnel until the approaching bus drivers are aware of the situation through communication or ability to sight the fire themselves. There are two scenarios which were analysed within the recognition phase. The two scenarios chosen are based upon historic events and technological capabilities and can be seen in Figure 37. Following the description of the two scenarios, a description will be given into the human behaviours that occur within the response stage.

The first scenario will be defined by the recognition of the fire by the bus driver where the second scenario is defined by the bus driver not initially recognising the fire.

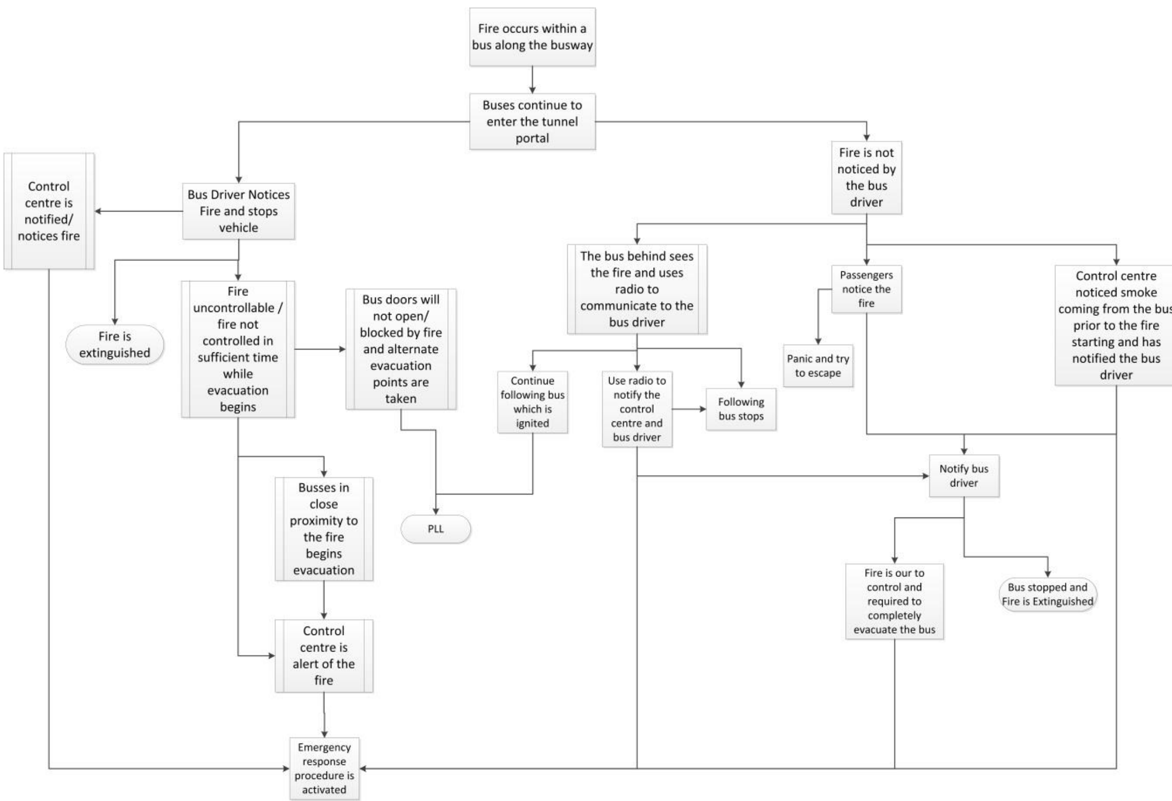


Figure 37 - Scenario 1 & 2

11.4.1 **Scenario 1**

The first scenario involves the fire initially being noticed by the bus driver. This situation assumes that the bus is the first to know about the fires occurrence and has the following possibilities;

1. The bus fire is extinguished
2. Control centre is notified/notices fire
3. The fire quickly becomes uncontrollable/the fire is not controlled in sufficient time while evacuation begins.

The bus fire could be quickly extinguished if the bus driver has sufficient training or is aware of the situation or alternately if there is a commuter who has good situational awareness or experience. If the fire isn't extinguished quickly then it could get out of control. In the event of the fire becoming out of control there is a possibility of the bus doors becoming jammed or becoming blocked by the fire (has been seen to occur within historic events). The jamming/blocking of the door would lead to panic and use of alternate evacuation points. The inability to escape could lead to potential loss of life. When the control centre is notified (by a bus driver) or they notice the fire by use of their information and control system, they can begin the emergency response procedures. The more thorough the operators training and understanding of the procedure, the faster the actions can be carried out to ensure tunnel users are in a place of safety before conditions worsen.

Following the evacuation of the bus which is on fire the surrounding buses are assumed to realise the severity of the situation and either the bus driver instructs the passengers to evacuate the tunnel in an orderly manner of people begin to self-evacuate. The evacuation process risk increases as the time to begin evacuation increases. As there are many combustible engines and petroleum fuel tanks it is critical to evacuate all personal as soon as possible.

The casual factors that can be extracted from scenario 1 are;

1. The fire becoming uncontrollable
2. Doors blocked

11.4.2 **Scenario 2**

In the case that the fire is not noticed by the bus driver, there is a possibility the following bus will notice the fire, passengers will notice the fire or the operation centre will first notice the event.

In the case that the following bus notices the fire they could notify the ignited bus driver along with the control centre. While notifying the driver they could simultaneously stop the bus and begin evacuation of the passengers through the fire isolated exits. In the event that the bus driver does not have proper training into how to deal with the situation, the following bus could stop or continue to follow the bus that is ignited without notifying anyone, in the hope that the ignited bus would notice. Once the Bus driver in the ignited bus was aware of the situation they could come to a halt and extinguish the fire using the on board, portable fire extinguisher.

If the passengers were the first to notice the bus fire it is possible that panic would occur. This panic could lead to erratic behaviour where passengers try to escape from a moving bus through the emergency exits such as the Huguenot tunnel, South Africa 1994 see

Appendix 2. This could have carryover effects to oncoming busway traffic and could lead to worsening the situation (e.g. a busway crash). Alternatively the passengers could simply notify the bus driver whom could stop and extinguish the fire, or in the event that the fire is already out of control the emergency response procedure could be carried out.

If the control centre was the first to notice the fire/smoke being emitted from the bus through the use of CCTV or the fire detection system, they could immediately notify the bus driver and simultaneously begin the emergency response procedure.

The Casual factors from scenario 2 consist of:

1. Bus following an ignited bus
2. Control centre not notifying the relevant stake holders
3. The fire detection system not working
4. Panic by the tunnel users or staff

11.4.3 **Following the Emergency response procedure**

Prior to emergency response, there is a lead up of events that is described in scenario one and two. A general observation can be made that the longer the time taken for the operation centre to notice a fire the longer will be the egress time for tunnel users and higher the risk.

Once the emergency response plan has been put into place there is again many choices and sequences that could occur. Emergency response arrival time, and efficiency of tunnel user egress, is based on the time that is taken for the operation centre to notice the fire and enter into the emergency response plan. The tunnel users can behave in different ways when the alarms, way finders and pre-recorded public announcement system are activated. The tunnel users can choose to ignore the automated system and check for survivors in the bus as the Sydney harbour tunnel case study revealed was a likely outcome within a real fire. The tunnel users might not follow the instructions as they are confused due to unclear instructions, or they might be experiencing the site effects of the smoke and heat from the fire and unable to make good decisions. In response to the passengers being confused or affected by smoke, they could receive instructions from the bus drivers on the ways to evacuate or they could follow the crowd which is already egressing towards the fire isolated exits. Depending on the awareness, location and characteristics of the individual the individual can also follow the procedures promptly and egress quickly. In some cases the tunnel users may have already egressed before the emergency response procedures has been carried out. When users reach the exit they may experience ease of egress and be able to exit promptly, they may experience queuing where people have filled the fire isolated tunnels and must wait to enter the tunnel, during the time that the user takes to get from the evacuated bus to the fire isolated exits the user may experience problems with vision and lack of oxygen.

When the emergency services is notified of the fire, depending on their location at time of notification they can arrive on site quickly or in an elongated period of time. Depending on the characteristics of the fire (ventilation controlled or fuel controlled) the time taken for emergency service to reach the site may inhibit the ability for the fire brigade to extinguish the fire. The tunnel operators must ensure that the tunnel operations do not fuel the fire and hinder the operations by the emergency services.

The casual factors that can be extracted within the response phase include;

1. Ignore signals
2. Elongated arrival time for emergency response

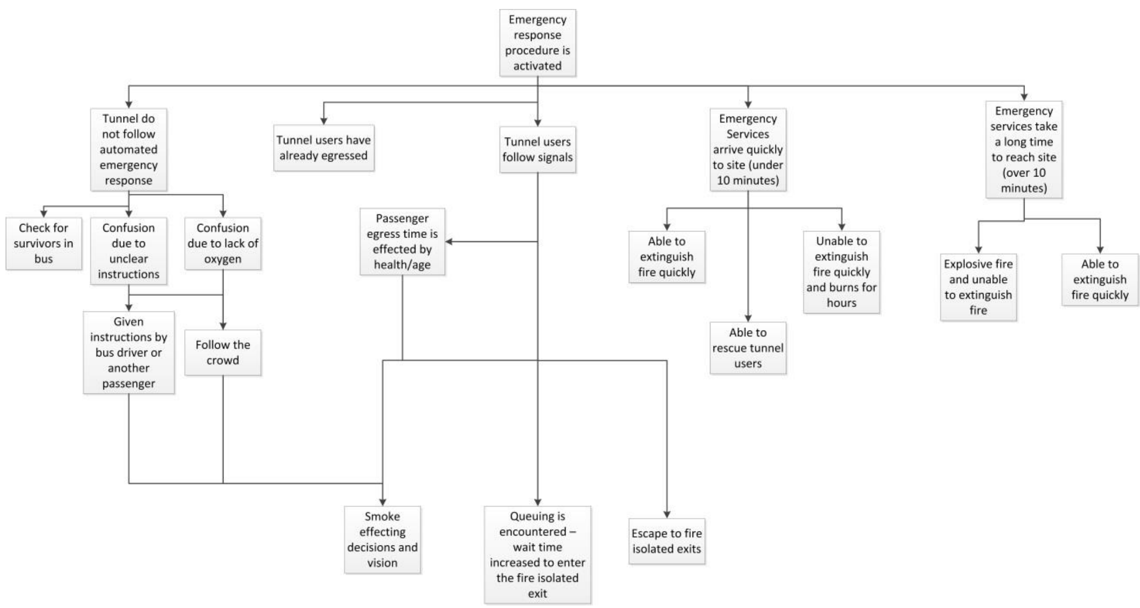


Figure 38 - Response phase

11.4.4 **Busway Root Causes**

Following the completion of casual factor charting, the casual factors can be extracted and the underlying root causes can be explored. They are considered to be the cause of potential human decisions that result in fatality within the BaT tunnel. The means of fatality within the busway are:

- Death due to Heat exposure
- Death due to smoke Inhalation
- Death due to Trampling

The casual factors that were highlighted within the casual factor charting were:

1. The fire becoming uncontrollable
2. Doors blocked
3. Bus following an ignited bus
4. Control centre not notifying the relevant stake holders
5. The fire detection system not working
6. Panic by the tunnel users or staff
7. Ignore signals
8. Elongated arrival time for emergency response

The fire becoming uncontrollable is the first casual factor that was identified. The process flow of the root causes are identifying in Figure 39. The root causes of the fire becoming uncontrollable can be related back to human behaviour. These Root cases consist of:

1. Insufficient training
2. Forget training
3. Insufficient maintenance
4. Information and control system error
5. Lack of communication
6. Insufficient fire identification technology

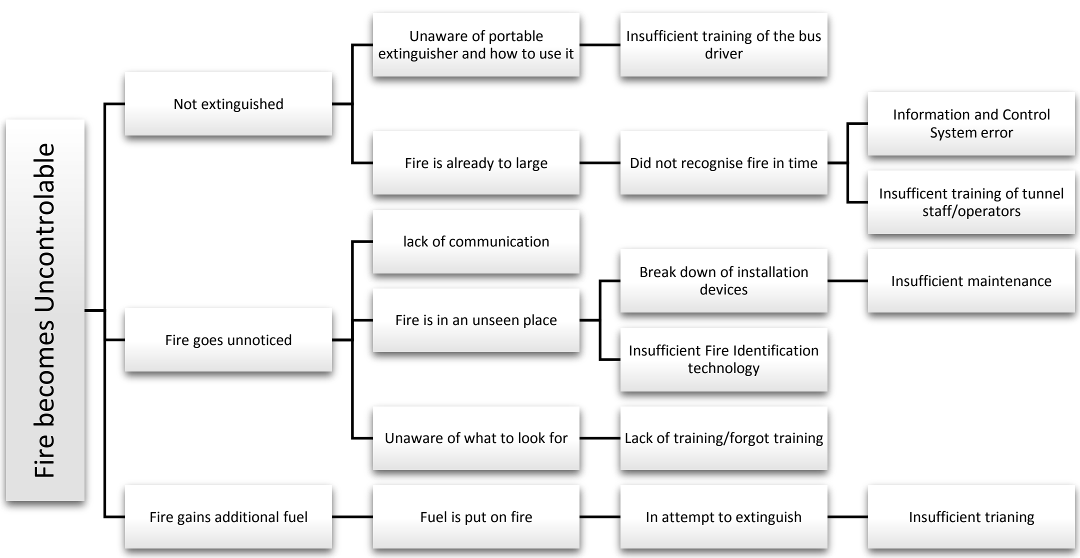


Figure 39 – Busway casual Factor 1 - Fire becomes uncontrollable

To mitigate the fire becoming out of control a number of recommendations can be implemented. Firstly the insufficient training involved with authority figures can be improved through re-examining the training program and ensuring that sufficient training material and programmes are provided. Feedback should be gathered from all members that participate within the training and appropriately acted upon. The fire safety officer should be responsible for liaison between tunnel staff/bus drivers and ensuring they are comfortable with procedures in the event of a fire. To ensure that the training is not forgotten it is recommended to produce material that can be kept by the individual and revised when needed, it is also important to have regular training to ensure that new processes are implemented sufficiently and information is not forgotten over time. It is important to produce flowcharts of the steps involved within emergency response for reference during the event of an emergency; these flowcharts should be kept in accessible places by all staff.

Insufficient maintenance can be due to personality, insufficient training and/or insufficient maintenance plans. The maintenance plans should be revised to ensure that there is sufficient documentation surrounding:

- The intervention level at which maintenance should be carried out
- The service levels VS the defect
- Units of measurement for usability of asset elements
- Frequency of inspections
- Possible inspection level
- Ability to revise the maintenance plans

The maintenance history should be sufficiently documented to ensure that there is not failure of the system upon change in staff and to ensure the maintenance plan is followed. Documentation is also important in recognising failure patterns. The maintenance can be carried out by contractors and hence there is the ability to check their standard of work. In the case that the maintenance is carried out by a tunnel staff member, there should be cross checking to ensure all duties are done to a correct standard.

Lack of communication between the operation centre and the bus driver during the event of a fire can cause the fire to become out of control. The communications process should be reinforced during training and the relevant stake holders position needs to be defined. To simplify communications a generic number could be provided for all to contact in the event of a fire where the staff member on the receiving end would be required to make relevant communication to all parties.

Fire Identification technology should be located in places that ensure fires are identified and the least cost is spent on the technology systems. There is a level of accepted risk with all pieces of infrastructure and hence it is important to plan the relevant safety level.

Another casual factor that contributes to fatalities within tunnel fires is the blockage of doors. The flow of root causes and the lead up to a door blockage can be seen in Figure 40. The root causes were attributed to the following reasons:

1. Personality
2. Lack of training
3. Fire characteristics

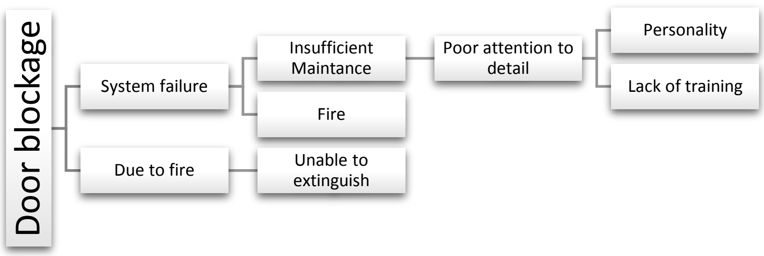


Figure 40- Busway casual Factor 2 - Door Blockage

Door blockage can be mitigated through ensuring quality staff are hired to carry out maintenance duties and that they are carried out in accordance with the maintenance plan. The staff should be trained in the use of portable extinguishes to try and prevent the fire getting to a stage that the system will fail.

Following an ignited bus is a casual factor that contributes to fatality in the event of a tunnel fire as there is an increased risk with the production of heat and smoke. The root causes of this action can be seen in the schematic within Figure 41. The root causes consist of:

1. Poor vision
2. Lack of training in fire science
3. Lack of training in emergency prevention
4. Distractions

Figure 41 - Busway casual factor 3 - Following an ignited bus

To reduce the likelihood of not noticing a fire, bus staff would be recommended to take a medical assessment prior to employment and effective treatment implemented. It should be ensured that adequate training is implemented and bus drivers take regular breaks to ensure concentration.

When Control centre do not notify the relevant stake holders, there is the possibility of the potential loss of life. The logic of the root causes can be followed within Figure 42 and consist of:

1. New staff
2. Sick staff
3. Personality
4. No updates to procedures

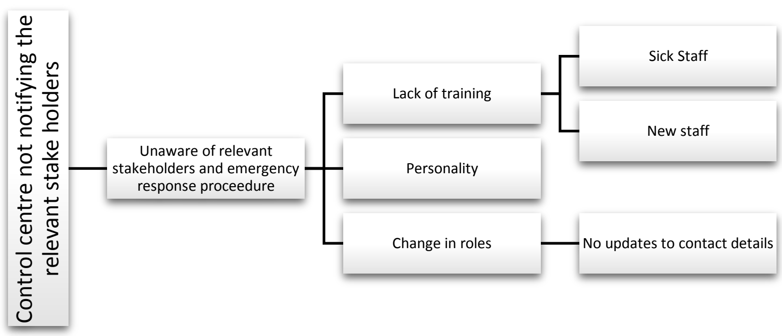


Figure 42 - Busway casual factor 4 - Control centre not notifying the relevant stakeholders

There should be adequate staff to ensure that new staff is not left in control. To get to positions that require experience there should be a progression plan and relevant experience will be required. Psychometric testing should be undertaken to ensure the staff are capable of fulfilling the duties required.

The failure of the fire detection system is a casual factor the attributes to the potential loss of life. The root causes can be defined within Figure 43 and consist of:

1. Lack of attention to detail
2. Not aware of maintenance problem

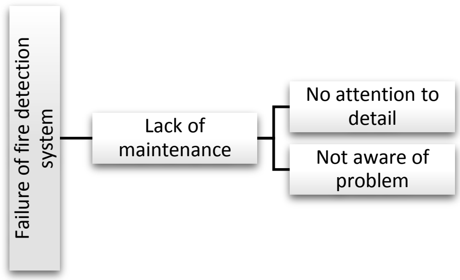


Figure 43 - Busway casual Factor 5 - Failure of fire detection system

As discussed above the maintenance should be adequate to ensure the efficient functioning of the tunnel and within this instance prevents the failure of the fire detection system.

Panic by tunnel users and staff can cause fatality within a tunnel fire. The root cause sequence of events is seen within Figure 44. The underlying causes of the panic can consist of:

1. Personality
2. Unclear instructions
3. Lack of education and training

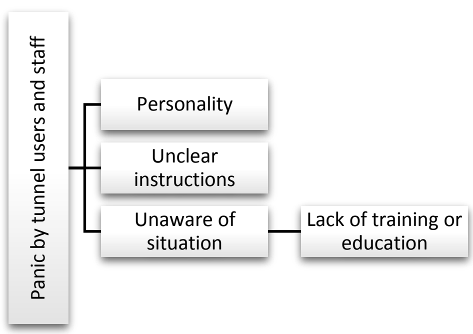


Figure 44 - Busway casual Factor 6 - Panic by tunnel users and staff

Panic can be mitigated against by effective training to ensure that those involved understand the procedures to follow and ensure they are comfortable with procedures. The bus drivers will be responsible to the egress of the bus users and instructing them to follow the procedures which is hoped to reduce panic. There is a risk of unclear instructions which can be reduced through practice.

Another casual factor that leads to fatality is ignoring the alarm system. The root causes of ignoring an alarm system are highlighted within Figure 45. These root causes consist of:

1. Unclear instructions
2. Lack of training or education
3. Check for survivors
4. Unclear communication
5. Language barrier

6. Age/health
7. Smoke exposure

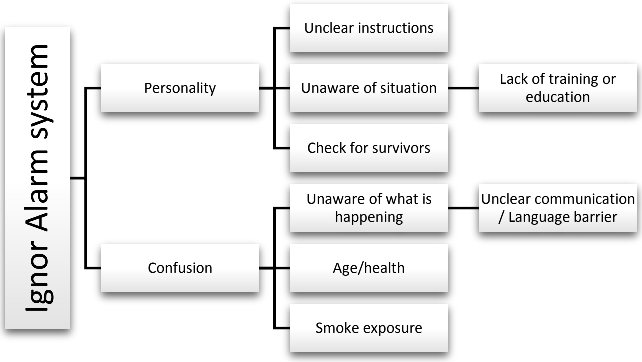


Figure 45 - Busway casual factor 7 - Ignore alarm system

To prevent alarms being ignored there must be influence upon their personality and a reduction in the confusion encountered during the time of egress. To increase the situational awareness of the tunnel users and to increase the chances of response educational campaigns can be rolled out to educate the public about the importance of egress. The effects of unclear communication and language barriers can be reduced through the use of internationally recognised signs and hand gestures.

The final casual factor that contributes to fatality within the busway is the Elongated arrival time for emergency response. The logic behind this cause is explained within Figure 46. The root causes consist of:

1. Time to notify Emergency services
2. Bus continuing to enter the busway
3. Smoke
4. Location

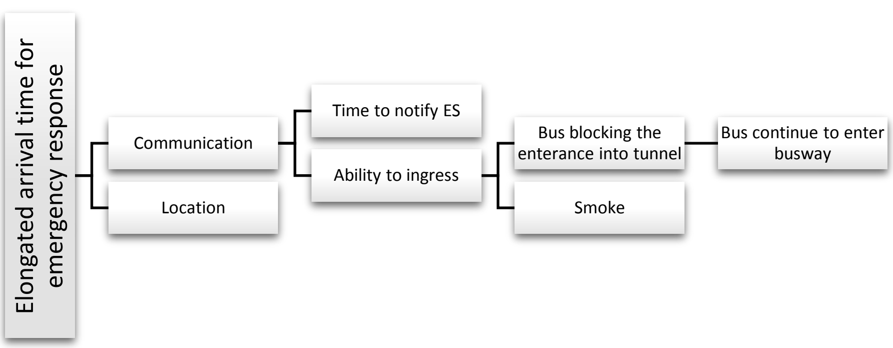


Figure 46 – Busway casual factor 8 - Elongated arrival time for emergency response

To reduce the time taken to notify the appropriate stakeholders the communication system should poses a degree of automation. The emergency response plan should be carried out as soon as possible. The location of the fire cannot be controlled however for effective entry the emergency response needs to be fully updated on the characteristics of the tunnel fire which requires effective communication. To allow for effective communication to the emergency response team a relationship should be formed between representatives of the emergency services and the operation staff.

To ensure that all casual factors have recommendations associated with them the following layout in Table 17 will be followed to display the results.

Table 17- Summary of results for the busways Root cause analysis

Casual Factor	Paths through root cause maps	Recommendations
Fire becomes uncontrollable	1. Insufficient training/ Forget training 2. Insufficient maintenance 3. Information and control system error 4. Insufficient fire identification technology 5. Lack of communication	1. To improve training and the ability for staff to remember the training, the training program should be revised regularly 2. Insufficient maintenance can be a result of insufficient training or personality and should incorporate well developed training programmes, goods and services management plan, and the ability to supervise the work of the maintenance staff 3. Information and control systems should include careful consideration of the placement of installations and a backup/redundancy system. The ability to alert humans in the event of a system are not operating at its full potential should be developed into the system. 4. The tunnel should have sufficient fire detection technology and develop an asset replacement schedule. The fire detection technology should be placed in areas that are prone to bus fires i.e. at the bottom of a gradient and so that there is ability to sense fires throughout the fire. 5. To ensure the communication process is more reliable, the alert system should be automated in addition to manual communication. There should be well defined definitions of roles, accessibility of all staff to information on who to contact in the event. There should also be requirements of relationship development within job descriptions i.e. develop relationships with the fire brigade.
Door Blockage	1. Personality 2. Lack of training 3. Fire characteristics	1. Flow charts of what to do in the event of a fire should be provided within the bus 2. Signs within a bus and within the tunnel should clearly indicate the location of firefighting equipment. 3. Bus drivers condition of use should be the ability to effectively extinguish fires with portable extinguishers 4. Bus driver trained with the ability to lead bus users through alternate exits
Following an ignited bus	1. Poor vision 2. Lack of training in fire science 3. Lack of training in emergency prevention 4. Distractions	1. A health test - involving eye site tests - should be completed prior to being hired as a bus staff member to ensure the driver is capable of seeing 2. The training should include information about fire and its effect upon tunnels, the places fires commonly occur and the ability to communicate the problem to bus drivers should be provided both as take home material and during face-to-face training. 3. Regular breaks should be taken to ensure the drivers can concentrate
Operation centre not notifying the relevant stake holders	1. New staff 2. Sick staff 3. Personality 4. No updates to procedures	1. New staff will be required to undergo sufficient training before work commences. Depending upon the positing – a cross over period may be required. 2. It is important to have sufficient staff to fill in for those whom are sick 3. It is important to have continuous updates in procedures to ensure all changes are documented including the changeover of staff 4. Must reinforce the importance of communication during operation
Failure of fire detection system	1. Lack of attention to detail 2. Not aware of maintenance problem	1. Reinforce the importance of attention to detail during training 2. Ensure scheduled monitoring and maintenance that follows a maintenance plan to ensure the integrity of the fittings within the tunnel
Panic by fire users and staff	1. Personality 2. Unclear instructions 3. Lack of education and training	1. Provide training to the staff to deliver messages in a clear and concise manor to ensure the staff feel comfortable in delivering the messages and to ensure the tunnel users are comfortable about being 'looked after'. 2. Provide advertising for the effects of tunnel fires within the BaT tunnel and highlight the importance of following instructions in a calm and orderly manner.
Ignore alarm system	1. Unclear instructions 2. Lack of training or education 3. Check for survivors 4. Unclear communication 5. Language barrier 6. Age/health 7. Smoke exposure	1. Pre-record and test the public announcement system to ensure it is audible and will be heard over the voices of people. While testing ensure the message that is being delivered is clear. 2. Provide advertising for the effects of tunnel fires within the BaT tunnel and highlight the importance of quick egress 3. Ensure training is given to the Bus drivers and staff with examples on what to say during an emergency 4. Ensure internationally recognised signs are used within the bus and train to ensure deaf and international tunnel users can understand. Where appropriate hand signals may be used. 5. Staff should encourage tunnel users to assist those whom are not capable of self-egress 6. Egress as quickly as possible. Ensure adequate training of the ventilation control staff to ensure they do not make the problem worse.
Elongated arrival time for emergency response	1. Time to notify Emergency services 2. Bus continuing to enter the busway 3. Smoke	1. Ensure training is undertaken and the idea of effective communication is reinforced 2. Training staff to look for signs and how to react to them. Consider the use of measures such as seen in Figure 17 - Sydney Harbour Bridge stop signals (Burns et al. 2013) 3. Ensure adequate training of the ventilation control staff to ensure they do not make the problem worse.

11.5 RAILWAY ROOT CAUSE ANALYSIS

The Root Cause analysis for the railway tunnel fire will be conducted in the same process as seen in the busway analysis (section 11.4). The RCA will consist of casual factor charting, root cause identification and the producing recommendations.

Casual factor charting is a process of listing the sequence of events that could lead up to a failure. This process will be carried out for the fire scenario described in section 11.1 in relation to human behaviour and how the sequence of events could occur within the rail tunnel. Following the casual factor charting, the root causes will be extracted. The root causes will be considered to be the cause of a decision made which lead to the potential loss of life.

The casual factor charting was undertaken for the railway and is displayed in Appendix 4. The process begins with a fire occurring in the busway; the potential reactions following the fire ignition will be documented and explained. There are two stages that occur within tunnel fires which consist of recognition and response. Both of these phases will be analysed and recommendations will be given for both scenarios.

11.5.1 Casual factor charting

The phases involved with tunnel fire response include recognition and response phases. These phases will be documented and displayed within Appendix 4.

Initially a fire begins within a cabin of the train. Two outcomes could pertain from such an event; the operation centre notices the fire or alternatively the operation centre does not notice the fire.

In the event that the operation centre does notice the fire the following sequence of events could occur. The operation centre notifies the train driver, begins the emergency response plan or the operation centre do not/cannot notify the train driver of the fire. When the operation centre notifies the train driver it is expected that he will notify the passengers via the public announcement system and begin to stop the train for passengers to egress. There is however, the possibility of the train driver not notifying the passengers causing the passengers to panic and try to change between the trains cabins or attempt to escape via breaking the glass.

If the operation centre was not able to contact the train driver or there was a break down in the communication process, the passengers or train driver may notice the fire. In the case the passengers notice the fire first there may not be sufficient means of communicating with the train driver and hence they may have to self-egress.

Once the emergency response plan and evacuation process has begun the passengers can experience the blockage of doors or the effects of smoke. In both cases staff members can assist with egress. In the event that the passengers are trapped within the cabin there is a need to egress an alternate was and some may begin to break the windows. Once the passengers have escaped they may experience confusion as to what should happen. However as there is large numbers of passengers it is likely that those that are confused will follow the crowd or follow the instructions given by the train staff members.

The emergency services must enter the tunnel to fight fires and provide aid to those who require it (i.e. those who suffer from smoke inhalation). The ability to ingress significantly impacts the time in which emergency services can reach the site and help to extinguish the growing fire.

When the operation centre does not notice the fire there is the possibility that either the passengers will notice the fire or the drive notices. This will then follow the sequence of events describes before. See Appendix 4for more detail.

The casual factors from the chart consist of:

1. Breakdown in communication
2. Door blockage
3. Passengers do not want to egress
4. Smoke
5. Arrival time for Emergency response

It can be noticed that the railway fire has less variables associated with the egress and less casual factor associated with the process.

11.5.2 **Root Cause identification**

The first casual factor that will be discussed is the breakdown of communication. The logic behind the identification of the root causes is seen in Figure 47. The root causes identify as:

1. New staff
2. Poor training
3. Fire characteristics
4. Location

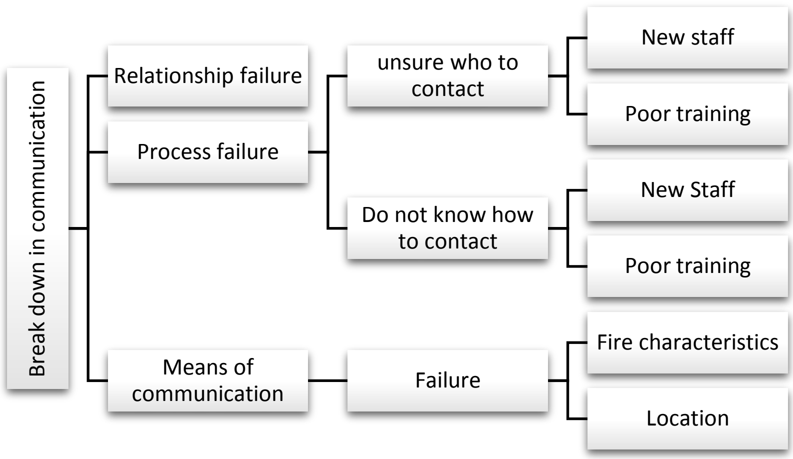


Figure 47- Railway casual factor 1 - Root cause identification

Following the identification of the root causes that result in a breakdown in communication, recommendations must be made to ensure the effects of new staff, poor training, fire characteristics and the location of the fire will be reduced. Just as the busway root cause analysis suggests, there must be sufficient training of new staff to ensure they comfortably and competently practices and carry out the tasks associated with the particular role. In some cases where much knowledge is needed a position may need to be filled from existing staff members. As fire characteristics could lead to the cause of communication failure, there is need to have back-up methods of communication, this could be inclusive of mobile phone, hand-held two way radio etc.

The second casual factor that will be discussed, which leads to the potential loss of life within the railway, is door blockage. This casual factor is similar to the occurrence within a bus fire. The logic behind the identification of the root causes is seen in Figure 48. The root causes were identified to be:

1. Personality
2. Lack of training
3. Fire characteristics
4. Inability to extinguish the fire
5. Fuel is added to the fire

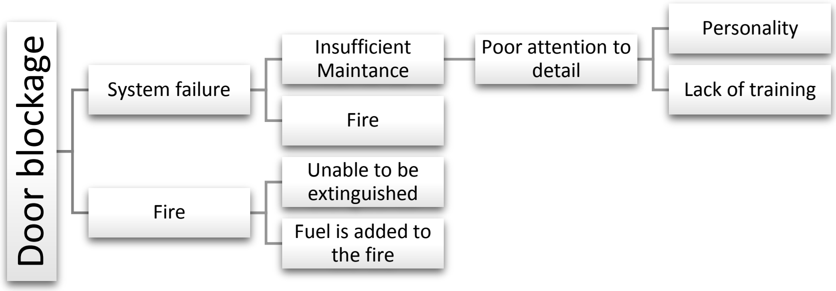


Figure 48 – Railway casual factor 2 - Door Blockage

Recommendations to reduce the effects of door blockage upon potential loss of life will be similar to that suggested within the busway root cause analysis. Hence, door blockage can be mitigated through ensuring quality staff are hired to carry out maintenance duties and that they are carried out in a timely manner in accordance with the maintenance plan. The staff should be trained in the use of portable extinguishes to try and prevent the fire getting to a stage that the system will fail.

The third casual factor that will be discussed is the passengers whom are unwilling to egress. This may be due to a number of reasons which are identified within Figure 49. The root causes were identified to be:

- Attachment to material objects
- Suicide
- Lack of education in fire science
- Lack of understanding of the question

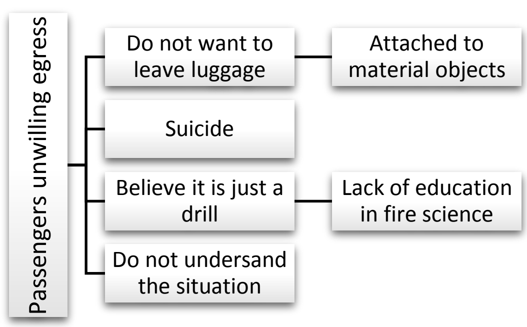


Figure 49 - Railway casual factor 3 - Passengers unwilling to egress

The unwillingness of passengers to egress can lead to fatality and hence a number of recommendations were generated to reduce this risk. Educating the public in the form of advertisements, posters and films about the severity of a tunnel fire situation along with informing about the effects of taking large personal items through to egress (refer to chapter 6.3.1.2). Staff should be trained in the ability to deal with suicide patients.

The fourth casual factor that pertains to fatality within the railway is the consequence of becoming effected by the smoke. This may be due to a number of reasons which are identified within Figure 50. The root causes were identified to be:

- Confined space within poor ventilation
- Unable to egress from train cabin
- Health/age

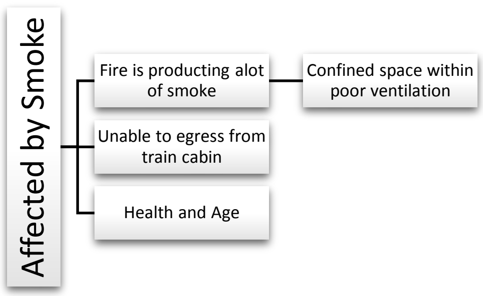


Figure 50 - Railway casual factor 4 - Affected by smoke

The main ability to reduce the effects of smoke lies within the time to egress and the ability of the ventilation staff to exhaust the smoke. Therefore it is important for the ventilation control staff to have a thorough understanding of the effects of fire and smoke. It is therefore important to have many simulations run for many different scenarios within finite element modelling.

The fifth and final casual factor that pertains to fatality within the railway is the consequence of elongated time for emergency response. This may be due to a number of reasons which are identified within Figure 51. The root causes were identified to be:

- Time to notify the emergency response
- Mode of transport used to ingress
- Smoke
- Safety of the emergency response team

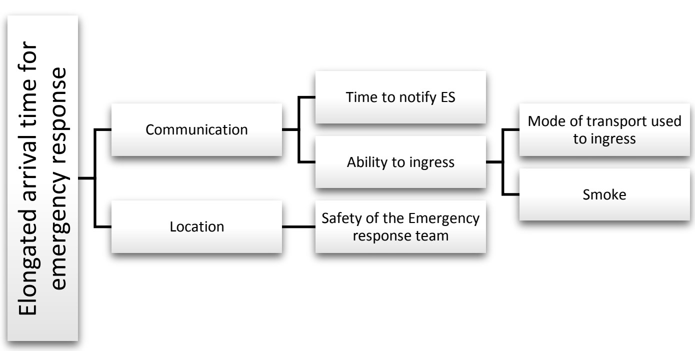


Figure 51 - Railway casual factor 5 - Elongated arrival time for emergency response

The ability to reduce the impacts of the elongated arrival time for the emergency services is related to both the communication and the location of the tunnel fire. The factors the can pertain to fatality within the event of a tunnel fire will involve the time taken to notify the emergency response team, the mode of transport used to ingress, the smoke that will be present upon arrival and the safety of the emergency response team. The effects can be reduced through effective education and training of the rail drivers, operational staff, ventilation controls staff and the emergency response team. This will allow for higher capabilities of the authority figures to communicate and control the tunnel fire (within reason) to allow for effective ingress of the emergency services

To ensure that all casual factors have recommendations associated with them the following layout in Table 18 will be followed to display the results.

Table 18 - Summary of results for Railway root cause analysis

Casual Factor	Paths through root cause maps	Recommendations
Breakdown in communication	1. New staff 2. Poor training 3. Fire characteristics 4. Location	1. New staff will be required to undergo sufficient training before work commences. Depending upon the positing – a cross over period may be required. 2. It is important to have sufficient staff to fill in for those whom are sick 3. It is important to have continuous updates in procedures to ensure all changes are documented including the changeover of staff 4. Must reinforce the importance of communication during operation
Door Blockage	1. Personality 2. Lack of training 3. Fire characteristics 4. Inability to extinguish the fire 5. Fuel is added to the fire	1. Flow charts of what to do in the event of a fire should be provided within the bus 2. Signs within a bus and within the tunnel should clearly indicate the location of firefighting equipment. 3. Bus drivers condition of use should be the ability to effectively extinguish fires with portable extinguishers 4. Bus driver trained with the ability to lead bus users through alternate exits
Passengers unwilling to egress	1. Attachment to material objects 2. Suicide 3. Lack of education in fire science 4. Lack of understanding of the question	1. Educational campaigns to provide information to the public about; the severity of a tunnel fire, the risk associated with evacuating along with large material items (i.e. luggage) 2. Staff should be trained in the ability to deal with suicide patients.
Affected by smoke	1. Confined space within poor ventilation 2. Unable to egress from train cabin 3. Health/age	1. The ventilation control staff needs to have a thorough understanding of the effects of fire and smoke. 2. Adequate simulations must be analysed in appropriate modelling software for many different fire designs to ensure the effects of smoke throughout the tunnel is understood.
Elongated arrival time for emergency response	4. Time to notify Emergency services 5. Bus continuing to enter the busway 6. Smoke	1. Ensure training is undertaken and the idea of effective communication is reinforced 2. Training staff to look for signs and how to react to them. Consider the use of measures such as seen in Figure 17 - Sydney Harbour Bridge stop signals (Burns et al. 2013) 3. Ensure adequate training of the ventilation control staff to ensure they do not make the problem worse.

12 DISCUSSION

This dissertation was conducted to develop an analysis of human behaviour which can cause fatalities within the Bus and Train Tunnel during a tunnel fire event. The purpose was to generate recommendations about the Bus and Train tunnels operations and design where applicable. Prior to the analysis the structural design was assumed to be sound, which allowed the analysis to be concentrated upon the human behavioural aspect when faced with a tunnel fire. The results generated from the analysis conducted within chapter 11, will be discussed in detail below. This will be followed by a discussion of the limitations within the study, and finally recommendations of future work will be made.

Prior to conducting the Root Cause Analysis (RCA) assumptions were made about the design fire, operations, and egress paths to give context and allow for effective analysis. The assumptions were based on Austroads operation and maintenance guidelines for road tunnels, the prescriptive tunnel standards AS4825-2011 and the documented, publically available information surrounding the BaT tunnel conceptual design. As the design information was assumed, it is not practicable to assume that the results can be directly applicable to the BaT tunnel design however from this study an indicative result was obtained.

12.1 DISCUSSION OF FINDINGS

Within history, buses have caused tunnel fires which have contributed to fatalities (review chapter 8.1). The cause of the bus fires is generally due to maintenance issues; hence the fires regularly begin within the engine and gearbox. It was clear from the analysis of the busway in chapter 11.4 that there are many factors that impact the potential loss of life. There is a difference between general road tunnels and the BaT tunnels busway in the mode of transport that is used within. The busway is used by bus-only mode of transport whereas the vehicles within road tunnels vary from dangerous goods vehicles through to poorly maintained personal cars. As the only vehicle entering the busway will be buses, there is ability for the public to be influenced by the bus driver and hence reduces the unpredictability associated with human behaviour in tunnel fires. However, the busway will be used by larger vehicles which have larger fire loads than road tunnels and also have a more densely populated tunnel due to the number of public transport users. The casual factors within the analysis were found to be:

1. The fire becoming uncontrollable
2. Doors blocked
3. Bus following an ignited bus

4. Control centre not notifying the relevant stake holders
5. The fire detection system not working
6. Panic by the tunnel users or staff
7. Ignore signals
8. Elongated arrival time for emergency response

These casual factors were then further analysed through a root cause analysis where the four main root causes were summarised and identified to consist of; communication breakdowns, slow reaction times, insufficient understanding and insufficient maintenance.

Within this study it has been highlighted that rail tunnel fires are less common than road tunnel fires, however the results are often far more devastating due to the large number of people in a small place and in some cases the inability to contact the train drive (such as the kaprun tunnel fire, Austria 2000). Within the BaT tunnels railway it was noticed that the critical factors that pertain to fatalities was similar to the busways causes of fatality. The results for the railway root cause analysis was summarised within Table 18. The summarised and identified root causes were found to consist of; communication breakdowns, slow reaction times, insufficient understanding and insufficient maintenance.

As the root causes are identical for both the busway and the railway, each component will be explained and the differences between the two modal sections of the BaT tunnel explained.

Firstly, communication is vital for the effective implementation of any procedure. Any breakdown in communication will lead to inefficiencies within the human system which then lead to higher risk, especially when operating in emergency response stages. The busway and railway can have breakdown in communication between the public, drivers, operating staff, stake holders, and Emergency services. A lack of communication can lead to confusion, panic and in some cases fatality. Examples of the impact of the breakdown in communication consists of the Kaprun rail tunnel fire in Austria, 2000 caused the death of 155 users due to the inability of tunnel users to communicate with the driver along with slow reaction times by the driver. To provide better communication it is recommended that redundancy is built into the system by providing multiple means of communication. It is recommended to have clearly defined management structure, clearly defined roles and the ability to access information on who to contact easily. The Øresundsbrun is an asset that is owned by both the Danish and Swedish government, which facilitates multimodal transport. The management structure is set up with clearly defined roles, with an external consortium that manages the finances for both states. It is recommended that the BaT tunnel develops a detailed management plan that allows all of stake holders to agree and maintain the integrity of the structure. Communication also plays an integral role with maintenance as it is important to document and communicate the need for maintenance to the correct authority figures. It is important to have ease of flow throughout the hierarchy of the tunnel users.

Acting within a timely manner is another vital aspect of tunnel fire safety within the busway and the railway. Figure 52 below shows the relationship between the actions that have to occur to egress and the increased time that each actions causes which potentially may cause the loss of life. It was mentioned within section 6.5 that the longer the time to egress the higher the chance of fatality. The busway and rail way can have a far more effective egress time than a regular road tunnel as staff are involved who have training in the egress of large amounts of people. However as bus and train can hold large amounts of commuters (especially in peak hour traffic) there could be impact upon egress time due to queuing. Figure 52 outlines the all considerations are related to time for egress.

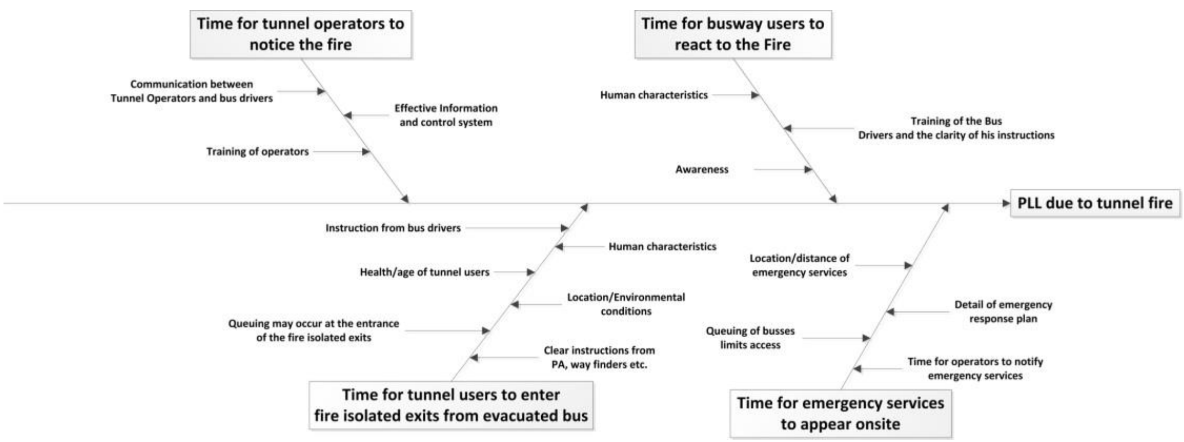


Figure 52 - Causes of fatality due to slow reaction times

Limited understanding of information surround tunnel fires (including the response plans, communication lines, fire science and evacuation plans) leads to poor decisions, breakdown in communication, slow response times and can cause maintenance problems. It is therefore important to have training of staff; including drivers, tunnel staff and operational staff. It is also important to educate the tunnel users through campaigns and advertising.

Maintenance needs to be provided to ensure the system is operating at its design potential at all times.

12.2 LIMITATIONS AND RECOMMENDATIONS

The BaT tunnel is an asset that incorporates both bus and rail public transport into a single tube. The BaT tunnel also includes underground stations. A major limitation of this study was the assumption that the entire system could be viewed in isolation. This means that the study did not conduct an analysis upon the stations and the busway and railway were effectively analysed as separate tunnels. This is an untrue account of the tunnel as in extreme circumstances there is possibility of the effects of a fire spreading throughout the 5.4km length of the BaT tunnel and may disperse into the stations. Hence for the completeness of work a study should be done into the human behavioural aspects that cause fatality within an underground station.

Another limitation to the study is the assumption of basing the tunnel design on publically available information and assuming unknown parameters to allow the study to be undertaken. This has meant that the recommendations may be incorrect or incomplete as the correct system was not analysed. Hence, in the future studies should be conducted which includes real data.

The study was done alone. Root causes are underlying problems that generally, are not focused upon. The fact that the study was conducted alone means that an input of ideas was not collated. The study would be more effective if a team of experience professionals and BaT tunnel design staff could perform a root cause analysis in unison. Hence, for completeness it is important to conduct the study with a group of BaT tunnel stake holders or authority figures.

The study is also limited as only 1 scenario for the bus and rail tunnel was analysed. There may be different reactions to a tunnel fire given a different scenario. The tunnel also does not look into the factor that location within the tunnel plays upon the behaviour of the individual involved.

The ventilation system plays an integral role to the characteristics of the fire within a tunnel. To analyse the effects of tunnel fires future work should include modelling of multiple scenarios to ensure the ventilation system can deal with the design fire adequately.

Constraints were met in conducting a full analysis due to confidentiality related issues. Therefore, in the future it is recommended to include information from international operation manuals.

13 CONCLUSION

The achievements of this study include:

1. Documentation of publically available information in relation to the BaT tunnel
2. Completion of a thorough literature review into tunnel fires, the risks they impose upon the tunnel structure and humans, contributing factors to tunnel fires and operation and maintenance of road tunnels
3. Rigorous data collection was undertaken into historic road and rail tunnel fires, tunnel fire case studies and data relating the fires within buses. Data was also collected into the management of a multimodal tunnel that involves two countries.
4. The use of a root cause analysis to provide recommendations to the BaT tunnel design in relation to the human behavioural aspects

This study has met the criteria it set out to achieve however there are many limitations that could possibly have skewed the results. The aim of the study was to provide recommendations to incorporate into the BaT tunnel through the use of a root cause analysis. Following the completion of the analysis it was found that the critical factors associated within the tunnels is communication, timely response, adequate understanding and thorough maintenance. It is therefore recommended that thorough training be provided to all staff, educational campaigns and advertisements should be utilised within the public domain and finally sound management should be established prior to operations.

The study conducted yields results to provide recommendations for use within the BaT tunnel design. There are however many limitations with the study and therefore to increase the accuracy of the results many more studies should be conducted for different fire design scenarios.

The findings show that tunnel fire related fatalities to decrease with the increased amount of knowledge the tunnel users have. The bus driver reduce the amount of fires within the busway in comparison the regular road tunnels.

14 APPENDICES

Appendix 1- Project specifications

University of Southern Queensland
Faculty of Engineering and Built Environment

ENG4111 and ENG4112 + Engineering Research Project 2014
Project specifications

FOR: **JACINDA BOULLY**

TOPIC: An analysis of human behaviour which can cause fatalities in the Bus and Train Tunnel during a tunnel fire event.

SUPERVISOR: **Ms Jo Devine**
Lecturer, Construction Engineering and Management, USQ School of Civil Engineering and Surveying

Mr Gavin Nicholls
Executive Director (Technical) | Underground Bus and Train
Major Planning Projects | Department of Transport and Main Roads

ENROLMENT: ENG4111, D, Sem 1 2014
ENG4112, D, Sem 2 2014

PROJECT AIM: The project aim is to use the Root Cause Analysis framework to develop recommendations for the Bus and Train tunnel design with respect to fire safety.

PROGRAMME: (Issue B, 24th October 2014)

1. Document relevant, publically available characteristics and proposed operations for the planned BaT tunnel
2. Conduct a literature review of tunnel operations and fire safety in tunnels, with particular reference to human behavioural aspects
3. Data gathering from international documented studies and fire safety literature. The data will reflect statistics of historic tunnel fires. The data will include case studies which highlight important aspects for consideration within tunnel fire safety. The data will include statistics upon the causes of tunnel fires.
4. Conduct a root cause analysis pertaining to fire safety in tunnels, in the context of the proposed BAT tunnel design and operations
5. Identification of important factors for consideration with regard to fire safety in bus and train tunnels
6. Produce recommendations for consideration in the final design of the BAT tunnel emergency response operations

Tunnel	Year	Mode	Load	Cause	Other information
Couronnes underground railway/metro station, France	1903	Rail	Passenger	Electrical Fault	84 deaths were estimated
Batignolles tunnel, France	1921	Rail	Passenger	Collision & use of gas lights	28+ people died
St Gothard, Switzerland	1941	Rail	Passenger	Derailment	7 fatalities
Torre Tunnel, Spain	1944	Rail	Passenger	Multi train collision	91 fatalities
Holland Tunnel, NY, USA	1949	HGV	-	Shedding its load	• No fatalities • 10 HGV's destroyed • 13 cars destroyed • 66 people injured
Stockholm underground railway/metro, Sweden	1955	Rail	Passenger	Overheating	• Carriage was destroyed
London underground metro, UK	1958	Rail	Passenger	Unknown	• 1 fatality
London underground metro, UK	1960	Rail	Passenger	Arcing in Receptacle box	• No fatalities • 38 passengers suffered from smoke inhalation
Stockholm underground railway/metro, Sweden	1960	Rail	Passenger	Short circuit	-
Blue mountains tunnel, USA	1965	HGV	Fish oil	Engine fire	• No fatalities • HGV was destroyed
Suzaka Tunnel, Japan	1967	HGV	Polystyrene boxes and other combustible materials	Unknown	• No fatalities • 13 trucks perished • Fire was extinguished after 11 hours • Inadequate operations
Moorfleet Tunnel,	1968	HGV	14t of polyethylene	Overheating (breaks)	• 1 hour

Germany			bags		
Simplon Tunnel, Switzerland-Italy	1969	Rail	Passenger	Unknown	• The carriage on fire was detached and the rest was driven safely away
Wallace Tunnel	1970	HGV	-	Engine fire	• No injuries
New York underground railway/metro	1970	Rail	Passenger	Unknown	• 1 fatality – a lady who returned to cabin in attempt to recover purse
Wranduk Tunnel, Yugoslavia	1971	Rail	-	Engine fire	• Extreme heat prevented passengers from exiting through the closest portal and hence exited through portal 1.3km behind
Crozet Tunnel, France	1971	Rail	1 goods train and 1 train carrying hydrocarbon	Collision and derailment	• 2 fatalities
Paris underground	1971	Rail	Passenger	Arson	• No fatalities • 3 injuries
Henri Bourassa railway/metro station	1971	Rail	Passenger	Collision with the end of a tunnel	• 1 fatality
Vierzy tunnel, France	1972	Rail	Passenger	Tunnel collapse	• 108 Fatalities
Alexanderplatz underground railway	1972	Rail	Passenger	Derailment	• No fatalities
Hokoriku tunnel, Japan	1972	Rail	Passenger	Fire in restaurant	• 30 Fatalities • 690 injured
Porte d'italie underground, France	1973	Rail	Passenger	Arson	• 2 Fatalities • Fire brigade were very quick
Moscow Underground	1974	Station	Passenger	Minor fire in metro station	• Passengers prevented from evacuating

					• No fatalities
Rosemont Underground, Canada	1974	Rail	Passenger	Short Circuit	• No Fatalities
Mont Blanc Tunnel, France/Italy	1974	HGV	-	Ignited	• No fatalities • Fire brigade arrived quickly
Chesapeake Bay Tunnel, USA	1974	HGV	-	Fuel tank of vehicles ignited from an exploding tyre	• No fatalities
Congress Tunnel, USA	1974	Rail	Goods	-	• No fatalities
New York underground railway, USA	1974	Rail	Passenger	Technical fault	• No fatalities • 78 people injured
Mexico City underground, Mexico	1975	Rail	Passenger	Collision	• 50 Fatalities
Moorgate Underground, UK	1975	Rail	Passenger	Collision with a wall	• 44 fatalities • 73 injured
Boston underground, USA	1975	Rail	Passenger	Broken Catenary	• No fatalities
Goodge Street, UK	1975	Rail	Passenger	Fire in cross passage	• No fatalities
Guadarrama Tunnel, Spain	1975	HGV	Pine resin	Ignition	• No fatalities • Thick toxic smoke • Fire lasted 2.75 hours
Chateau de Vincennes underground, Paris	1975	Rail	Passenger	Short circuit	• No fatalities
Finsbury Park underground	1976	Rail	Passenger	Cable fire	• No fatalities
Lisbon underground, Portugal	1976	Rail	Passenger	Electrical fire	• No fatalities • $1.8 million in damages
Porte d'italie Tunnel, France	1976	HGV	16t Polyester plastic	Engine fire	• No fatalities • 12 injuries • 1 hour fire
San Bernardino Tunnel, Switzerland	1976	Bus	Passenger	-	• No fatalities • Fast response from fire brigade
Christie Street Underground, Canada	1976	Rail	Passenger	Arson	• No fatalities

Paris Underground, France	1977	Rail	Passenger	Minor fire	• No fatalities
Baltimore Harbour freeway, USA	1978	HGV	-	Truck collided with a fuel tanker	• No fatalities
Mont Blanc tunnel, France/Italy	1978	HGV	-	Collision	• No fatalities
Velsen Tunnel, Netherlands	1978	HGV	-	Collision	• 5 fatalities
Hansaring underground, Germany	1978	Rail	Passenger	Fire	• No fatalities
San Francisco Underground, USA	1979	Rail	Passenger	Short Circuit underneath the train	• 1 fatality • 56 injured
Paris Underground, France	1979	Rail	Passenger	Short Circuit	• No fatalities • 1000 people to evacuate
Eric Street underground, USA	1979	Rail	Passenger	Transformer fire – train doors failed to open	• No Fatalities
New York underground	1979	Rail	Passenger	Cigarette ignited an oil spill within a station track	• No Fatalities
Nihonzaka Tunnel, Japan	1979	HGV	-	Collision	• 7 fatalities • Traffic congestion led to firefighting delay
Altora underground, Germany	1980	Rail	Passengers	Arson	• No fatalities • 4 injuries
Kajiwara tunnel, Japan	1980	HGV	200 cans of paint	Gearbox fire	• 1 Fatality
Saki Tunnel, Japan	1980	HGV	-	Collision	• 5 fatalities
New York underground, USA	1981	Rail	Passengers	Fault in current collectors	• No fatalities • Evacuated by breaking glass • Fire brigade arrived after 20 minutes and took 6 minutes to extinguish the fire
Okyabraskaya	1981	Rail	Passengers	Short circuit	• No Fatalities

underground, Moscow					
London underground, UK	1981	Rail	Passengers	-	• 1 Fatality
Ramersdorf underground railway/metro , Germany	1981	Rail	Passengers	Technical fault	• No fatalities
Mont Blanc tunnel, France/Italy	1981	HGV	-	HGV stopped 4.5km into the tunnel	• No injuries recorded
Washington DC underground, USA	1982	Rail	Passengers	Derailment	• No injuries
Caldecott tunnel, USA	1982	Passenger car	-	Drink driving – Collision into petrol tanker	• 7 fatalities
Piccadilly line, UK	1982	Rail	Passengers	Electrical cable	• No fatalities
Salang Tunnel, Afghanistan	1982	Military convoy	-	Explosion	• 176-3000 fatalities
Frejus Tunnel, France	1983	HGV	Plastic	Gearbox fault	• No fatalities • 2 hours to control fire
Hauptbahnhof Underground, Germany	1983	Rail	-	Electrical fault	• No fatalities
Percorile Tunnel, Italy	1983	Lorry	Fish	Collision	• No fatalities
Felbertauern Tunnel, Austria	1984	HGV	-	Break overheating	• No injuries • Fire lasted 1 hour
St gotthard tunnel, Switzerland	1984	HGV	Rolls of plastic	-	• Very fast response by emergency services • Fire burned for 30 minutes
Landungsbruken underground, Germany	1984	Rail	-	Arson	• No fatalities • $3 million worth of damages
Summit tunnel, UK	1984	Rail	Diesel and petroleum spirit	Derailed	• No fatalities • Fire contained by high expansion foam and water

San Benedetto, Italy	1984	-	-	Bomb attack	• 17 fatalities
Paris underground, France	1985	Rail	-	Rubbish fire	• No fatalities
Grand central station, New York	1985	Rail	-	Arson	• No fatalities
Mexico City underground, Mexico	1985	Rail	-	-	• 1700 injured
L'arme Tunnel	1986	Passenger cars	Trailer	Collision	• 3 fatalities
Herzogberg Tunnel, Austria	1986	HGV	-	Breaks overheating	• Oversized extraction of the ventilation system allowed for effective fire fighting
Gumefens Tunnel, Switzerland	1987	HGV	-	Collision	• 2 Fatalities • Fire burned for 2 hours
Brussels underground, Belgium	1987	Rail	-	Fire in station	• No injuries • 1000 evacuated
Moscow underground, USSR	1987	Rail	-	Fire on train	• No injuries
Tanzenberg tunnel, Austria	1987	Passenger car	-	Suicidal car driver	• No fatalities
Kings cross station, UK	1987	Station	-	Steps of wooden escalator fuelled fire and was thought to have begun by grease and fluff under the escalator	• 31 fatalities
Mont Blanc Tunnel, France/Italy	1988	HGV	-	Driver noticed smoke but did not stop until flames entered the cab	• Fire fighters arrived within 10 minutes
Roldal Tunnel, Norway	1990	Passenger car	-	Engine overheated	• No fatalities
New York underground, USA	1990	Rail		Cable fire	• 2 fatalities • Dense smoke • Wrong train evacuated
Hischengraben Tunnel,	1991	Rail	-	-	• No fatalities • Driver was

Switzerland					unaware of fire • After 2 minutes passengers were instructed to evacuate
Hovden Tunnel, Norway	1993	Passenger car	-	Collision of 2 cars and a motorcycle	• No fatalities • Significant damage to tunnel
Huguenot Tunnel, South Africa	1994	Bus	45 passengers	Gearbox	• Unknown amount of fatalities • 7 people jumped from moving vehicle • Fire was not extinguished when small and therefore grew • 12 minutes for fire brigade to reach the site
Castellar tunnel, France	1994	HGV	Waste paper	Exploding tyre	• No fatalities
St Gotthard Tunnel, Switzerland	1994	HGV	750 bicycles in cardboard boxes	-	• No fatalities • 2 hours to extinguish fire
Kingsway Tunnel, UK	1994	Bus	-	Fire	• No fatalities • Lasted over 1 hour
Hitra Tunnel, Norway	1995	Mobile crane		Motor fire	• No body injured • 2 hours to extinguish fire
Pfander Tunnel, Austria	1995	Passenger vehicle	-	Fatigue and collision	• No fatalities • Sufficient smoke hindering emergency response
Baku underground, Azerbaijan	1995	Rail	-	Electrical fault	• 260 Passengers died • Trouble opening doors • Entire tunnel

					filled with smoke in direction of evacuation • Tunnel reopened in 24 hours
Isola Delle Femmine Motorway, Italy	1996	Passenger car		Crash involving a petroleum tanker and explosion	• 5 fatalities • After 6 minutes there was an explosion
Washington, USA	1996	Rail	-	Short Circuit	• No fatalities • Failure to turn off electricity and to stop other trains
Ekeberg Tunnel, Norway	1996	Bus	-	Engine	• No fatalities • Fire lasted 2 hours
Channel Tunnel, France/UK	1996	Rail	HVG carrier shuttle	-	• No fatalities • Reached 350MW • Ventilation was thought to help fire grow • 7 hours to extinguish fire
Prapontin Tunnel, Italy	1997	HGV	Textiles	Breaks overheated	• No fatalities • Fire lasted 4 hours
Exilles Rail Tunnel, Italy	1997	Rail	216 cars	Door dragging along electrical wiring	• No fatalities • Fire fighters arrived 20 minutes later
Toronto Underground, Canada	1997	Rail		Rubber matting stored under the tracks in a shunting area	• No injuries • Thick black smoke
St Gotthard tunnel, Switzerland	1997	Car transporter		Engine fire	• No fatalities • 3 Hour fire
St Gotthard tunnel, Switzerland	1997	Bus	-	Engine fire	• No fatalities • Extinguished in 20 minutes
Gleinalm Tunnel, Austria	1998	Double decked coach		Short circuit	• No injuries
Gueizhou Tunnel, China	1998	Rail	Gas canister	Tunnel collapsed	• 80 fatalities
Leinebusch	1999	Rail	Paper and	Ball-bearing	• No fatalities

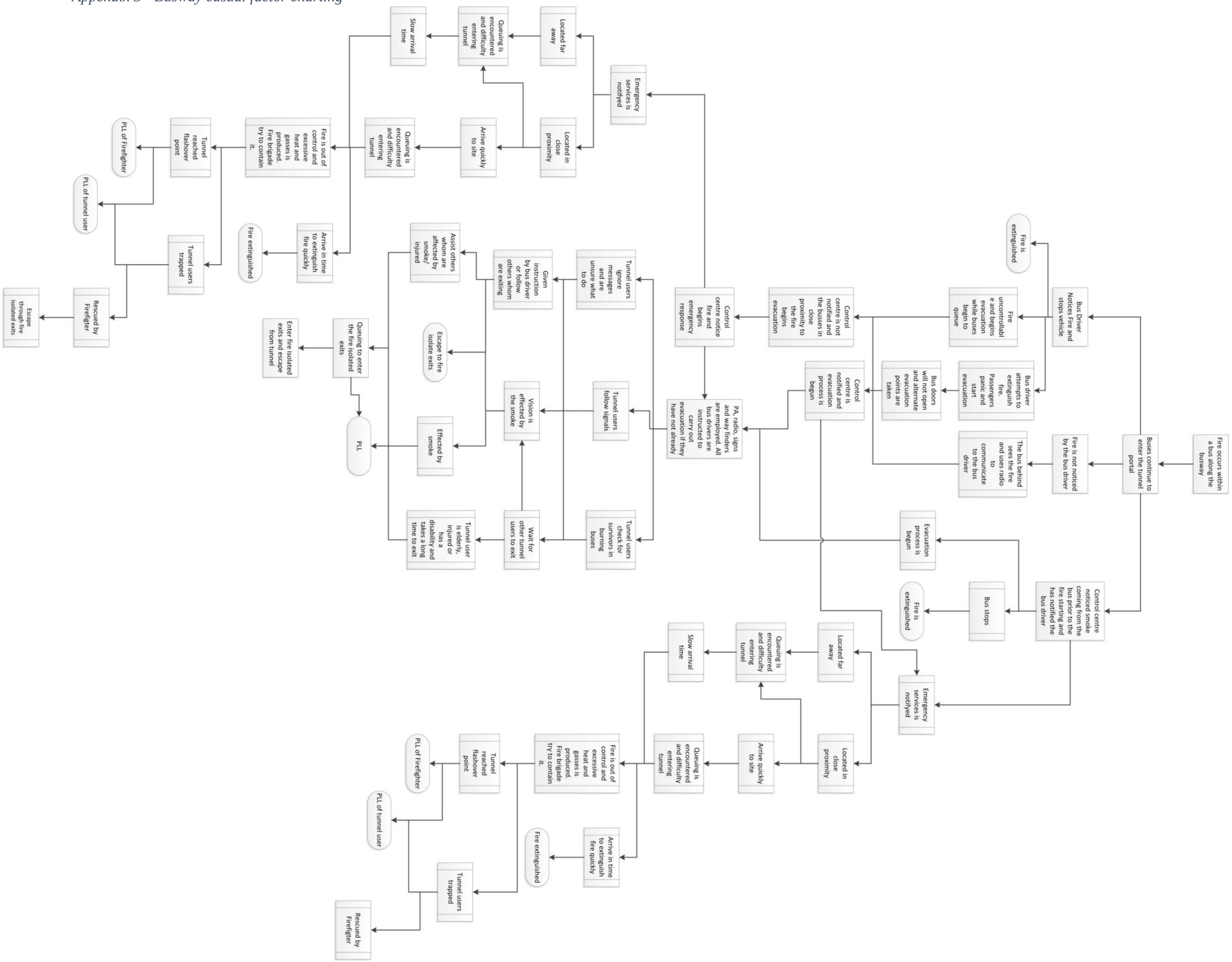
Tunnel, Germany			pulp	overheated	• 12 hours to extinguish
Mont Blanc Tunnel, France/Italy	1999	HGV	Margarine	Diesel fuel leaking	• 39 Fatalities • Poor operation of the ventilation system • Lack of communication between France and Italy
Railway Tunnel, Italy	1999	Rail	Football fans	Rowdy behaviour – Smoke bomb was lit	• 4 people died
Tauern Tunnel, Austria	1999	HGV	Spray cans	Collision	• 8 Fatalities
Montreal Underground, Canada	2000	Rail	-	Cable fire	• No fatalities • 6 tunnels filled with smoke • Triggered 3 explosions • Failure of electrical, communication and ventilation system
Cross Harbour tunnel, Hong Kong	2000	Passenger car	-	-	• No fatalities • Tunnel personnel were on the scene in 3 minutes • Fire brigade took 5 minutes to arrive
Berlin Underground, Germany	2000	Rail	-	-	• No fatalities • Smoke inhalation
Seljestad Tunnel, Norway	2000	Truck	-	Collision	• No fatalities • Fire destroyed the communication cables • Ambulance arrived in 15 minutes • Fire brigade arrived in 30 minutes

Rotsethhorn, Norway	2000	Road tunnel	-	Collision	• 2 fatalities
New York City Underground, USA	2000	Rail	-	-	• No fatalities • Firefighting took over 2 hours and 20 minutes
Saukopf tunnel, Germany	2000	Passenger car	-	-	• No fatalities • The fire brigade extinguished the fire easily
Oslofjord	2000	HGV	-	Minor incident	• No fatalities
Kitzsteinhorn funicular tunnel, Austria	2000	Rail	-	Hydraulic oil leaking	• 150 fatalities • Velocity of the ventilation was 10m/s
Laerdal Tunnel, Norway	2000	Bus	50 passengers	Small fire started	• No fatalities • Easily dealt with by the bus driver
Toronto underground, Canada	2000	Rail	Refuse from old mill station	-	• No fatalities
Dusseldorf underground	2001	Rail	-	-	• No fatalities
Prapontin Tunnel, Italy	2001	HGV	-	Unknown	• No fatalities • Smoke inhalation injuries
Kurt Schumacher Platz station underground, Berlin/ Germany	2001	Rail	-	Arc lamp	• No fatalities
Tauern Tunnel, Austria	2001	Passenger Cars	-	-	• No fatalities • Fire extinguished quickly by driver of car
Schipol Airport, Netherlands	2001	Rail	-	Electrical connection box in a rail tunnel	• No fatalities
Howard Street Tunnel, Baltimore, USA	2001	Freight train	Hazardous material	Detachment of cars	• No fatalities • Tunnel closed for 12 hours • Reschedule of Baseball games
Gleinalm	2001	Bus	Swedish	-	• Driver drove

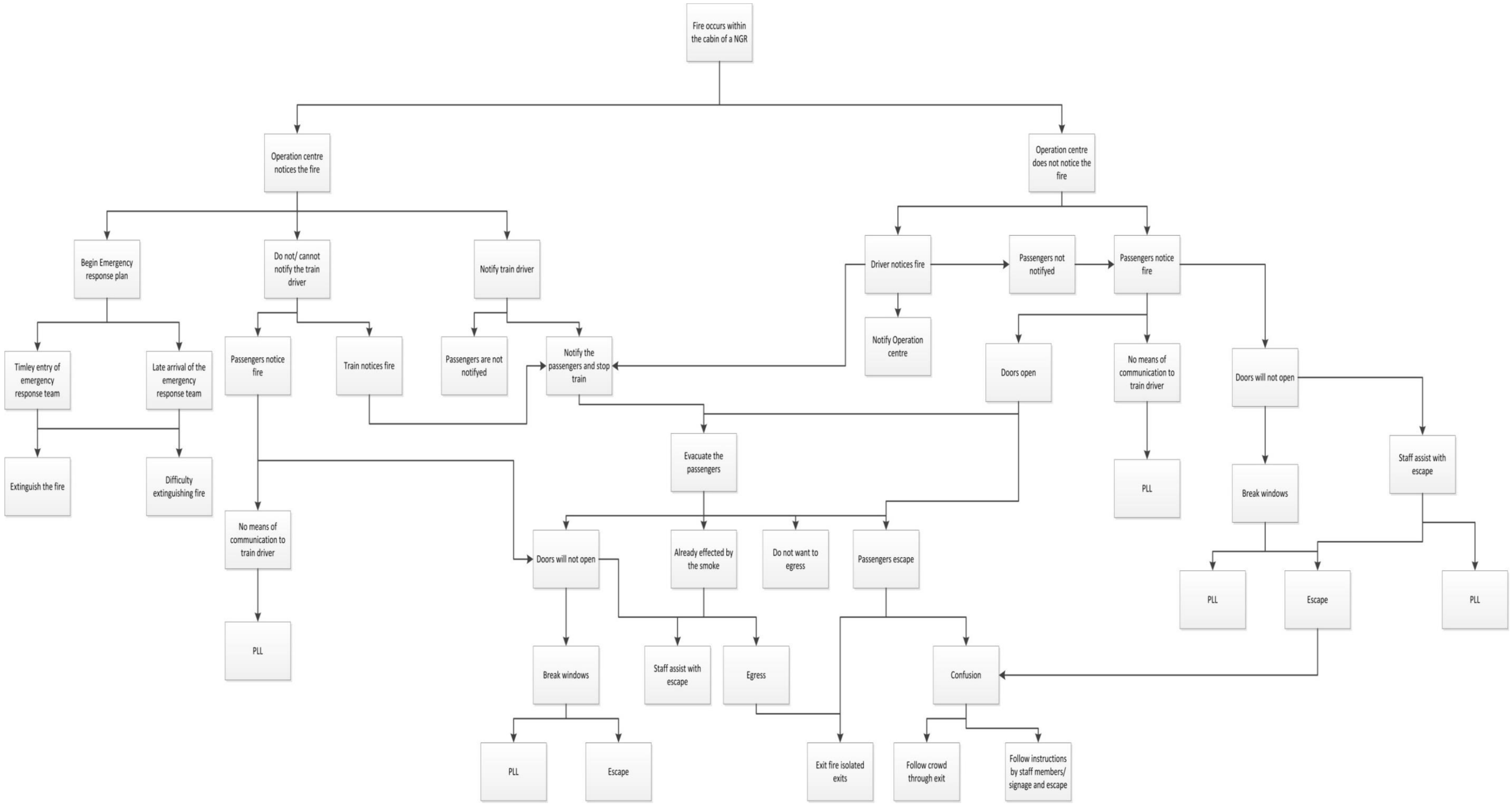
Tunnel, Austria			tourists		bus out of tunnel before stopping
Gleinalm Tunnel, Austria	2001	Passenger car	-	Head on collision	• 5 fatalities
Gleinalm Tunnel, Austria	2001	Bus	Tourists	-	• No fatalities • Tunnel closed until coach was removed
St Gotthard Tunnel, Switzerland	2001	HGV	Rubber tyres	Collision	• 11 Fatalities • 23 vehicles destroyed • Parallel service tunnel saved many lives • Fire burned for 2 days
Tauern Tunnel, Austria	2002	Lorry		Faulty engine	• No fatalities • Fire brigade under control very quickly
Ted Williams Tunnel, Boston, USA	2002	Bus	Seattle Mariners Baseball	Electrical compartment at the rear of the bus	• No fatalities • A lot of smoke but no damage to tunnel
Homer Tunnel, New Zealand	2002	Bus	Tourist	Engine Fire	• No fatalities • Bus rolled backwards

Jungangno underground, South Korea	2003	Rail	-	Arson- petrol and cigarette lighters	• Many Fatalities • After the operators were aware of the fire a second train entered the tunnel and the doors of the second train did not open
Cret d'eau Tunnel, France	2003	Rail	-	Within sleeper carriage of the train	• No fatalities • Lack of planned emergency evacuation procedures
Mornay Tunnel, France	2003	Rail	-	-	• No fatalities • Once fire detected train stopped immediately
Locica Tunnel, Slovenia	2003	HGV	Cargo	-	• No fatalities • 28 vehicles entered the tunnel after stop signal was displayed
Guadarrama Rail Tunnel, Spain	2003	Rail	-	-	• No fatalities • 34 workers were trapped and hid in an air pocket
Floyfjell Tunnel, Norway	2003	Passenger car	-	Veered into the wall	• 1 Fatality
Golovec Tunnel, Slovenia	2003	Bus	Fire fighters	Engine fire	• Able to extinguish fire • No fatalities
Dullin Tunnel, France	2004	Bus	-	Engine fire	• No fatalities • Drove bus to tunnel portal after noticing fire
Kinkempois Tunnel, Blgium	2004	HGV	-	-	• No fatalities • Safety systems operated appropriately

Appendix 3 - Busway casual factor charting



Appendix 4- Railway casual factor charting



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