Combined Qualitative and Quantitative Fire Risk Analysis – Complex Urban Road Tunnel

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Abstract

At the moment, there is some lack of consistency of how a risk analysis for a tunnel should be undertaken. A few countries have developed some methodologies; the Netherlands has developed a QRA-model called "TunPrim", in France a procedure called "Specific Hazard Investigation" has been developed. PIARC is at the moment working on some guidelines. However, there is a need for an established and recognized risk management process.

The type and level of risk analysis needed depends on the complexity of the tunnel and, of course, on the legal authorities (it needs to be established what level of risk analysis is required).

This thesis describes how a risk analysis was performed for an urban road tunnel and it suggests an approach for risk analyses for complex tunnels. It gives an example of how a risk analysis methodology for a tunnel could be undertaken.

The different steps of the Quantitative Risk Analysis (QRA) process are described and it is also shown how some mitigation measures affect the risk.

The difficulties and problems with QRA are discussed briefly. Areas for future research and development are proposed.

It is assumed that the reader is familiar with the basics of the risk management; event trees, FN-curves, risk matrices, risk measures etc.

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Executive Summary

This thesis describes how a risk analysis was performed for an urban road tunnel and it suggests an approach for risk analyses for complex tunnels. It gives an example of how a risk analysis methodology for a tunnel could be undertaken.

The main aim of the report is to show a usable methodology regarding risk analysis for tunnels.

The main aim of the analysis is to identify the different fire risks in the tunnel, ascertain if they are tolerable/acceptable and determine the potential benefit of additional mitigation measures.

The risk benchmarks developed are not directly used to determine if the risks are acceptable or not but more used to see how the fire accident risks and accidents risk criteria are in proportion to each other. By determining this it is possible to make an assumption about the risk level and in that way decide if the risks are considered tolerable or not. It is important to keep in mind that the risk criteria are considered aspiratory and not used directly to see if a risk is acceptable or not.

The risk level in the analysed part of the tunnel is found to be tolerable. The risk level is slightly higher than the aspiratory criteria established in Norway and Austria for urban road tunnel systems, but historical data seems to indicate that these conservative levels are generally not met.

If it was felt necessary to reduce risk further to approach the aspiratory levels mentioned above, one effective mitigation measure would be to restrict/eliminate heavy vehicles from the tunnel but the practicality of this should be carefully considered.

The report gives recommendations on minimum safety equipment installations that should be considered for the tunnel. Information received on safety systems planned for the tunnel indicate that in all cases the systems meet or exceed the recommendations.

The report shows that the main difficulty with QRA is the quality of data. Most variables used in the analysis are associated with uncertainties. For this analysis three main areas were recognized to be associated with uncertainties:

- Development of accident frequencies. Uncertainties associated with incident statistics.
- Probability figures for technical systems. Uncertainties associated with failure probabilities for detection systems, ventilation systems, etc.
- Development of consequence figures. Uncertainties associated with the prediction of fatalities.

1 Introduction

This report describes how a risk analysis was performed for an urban road tunnel and it suggests an approach for risk analyses for complex tunnels. The report only covers a specific part of a greater analysis, due to this it will not go into detail for some areas of the risk analysis; these are identified in the report.

The main aim is to show a usable methodology regarding risk analysis for tunnels.

1.1 Tunnel fires – Why so different

During recent years tunnel fires have obtained special attention, this is mainly due to a few catastrophic fires that have occurred in alp-tunnels (St Gotthard, Switzerland, 11 dead – 2001; Tauern, Austria, 12 dead – 1999; Mont Blanc, France/Italy, 39 dead – 1999).

Tunnel fires are different from other types of fires; their consequences can be larger due to their situation (underground).

A car fire on an open road rarely affect other people than the ones situated in the car on fire, smoke and heat produced by the fire dissipate easily, only a small area around the fire is affected. On the other hand a car fire in a tunnel could affect a large number of people, the smoke and heat produced by the fire could affect a great part of the tunnel, especially the smoke produced could travel very far within the tunnel.

There are several problems that are directly related to the nature of the tunnel. Evacuation from a tunnel is very different compared with evacuation from a building, the knowledge about what to do in these kinds of situations and how serious a tunnel fire could be has a great impact. Fire fighting is also different, it depends heavily on the type of access routes, the type of traffic, the smoke control strategy, etc. it is normally very difficult to fight fires and start life saving operations within tunnels.

The active measures used for a tunnel could have large impact on evacuation and fire fighting. The main issue is normally the production of smoke and its possibility to spread within the tunnel, for complex tunnels the smoke strategy is important. Another active measure, with different views around the world regarding the feasibility, is the use of suppression systems. A suppression system normally has a significant impact on the fire size and heat release rate but also on the behaviour of the smoke produced.

There is no doubt about that tunnel fires have the potential to be very serious and that there are great differences regarding evacuation and fire fighting when compared to open road or building fires.

1.2 Background

A large ring road around a European city is currently undergoing a major upgrade to improve traffic flows, to open up new areas for redevelopment and to improve the environment. Part of the works involves the lowering of different sections of ground level motorway into tunnels. The tunnels will free up land, enabling the creation of parklands with pedestrian access.

The tunnels vary in height, slope etc. as they dip and turn to accommodate existing on and off ramps, metro lines, main sewers, etc.

A fire risk analysis has been performed for some of the tunnels.

1.3 Aim of Report

The aim of the report is to show how a fire risk analysis for this type of tunnel can be done. A semi-quantitative analysis and a fully quantitative analysis have been undertaken.

The main aim of the analysis is to identify the different fire risks considered for the tunnel, ascertain if they are tolerable/acceptable and determine the potential benefit of additional mitigation measures.

The semi-quantitative analysis shows an approach that tries to establish if any sections of the inspected stretch of tunnel are expected to have a higher fire frequency due to their design. For example, sections with high gradients and closely spaced on and off ramps may be more susceptible to vehicle fires. The results of this analysis will give an indication of the necessity/importance to introduce mitigation measures in certain sections of the tunnel. Part of this analysis also serves to identify accident scenarios.

1.4 Methodology

The semi-quantitative analysis is quite simple and the methodology is explained later on in the report. The methodology explained below is aimed for the fully quantitative analysis.

The main methodology for the fully quantitative analysis can be described in three steps:

1. Risk identification
2. Risk evaluation
3. Risk elimination/reduction/control

In the first step the different hazards are identified and the risks evaluated: What could go wrong? How likely is it and what are the consequences? In the second step the risks are evaluated and decisions about if they are tolerable or not are made. The last step consists of finding ways of reducing or controlling the different risks.

More specifically the methodology used can be described as follows:

1. A qualitative or semi quantitative analysis is carried out. This analysis will identify the different accident scenarios used further on the analysis.
2. A fully quantitative analysis is carried out. The risks are quantified and the impacts on the risk level for the different safety/protection systems are evaluated.
3. The different risk mitigation measures are studied in more detail. The aim of this part is to determine which mitigation measures should be incorporated and how each one of them affect the risk level.

1.5 Scope and limitations

The results from this specific analysis are not applicable to the whole tunnel system. This analysis is only one part of a greater analysis.

Life safety aspects are considered, specifically related to fire. The main thrust is the safety of the tunnel users and the emergency services in fires.

Property protection and tunnel availability are considered to a much lesser degree.

Health and environmental aspects are not formally addressed.

Fire frequencies and probabilities used in the analysis are mainly based on statistical data from traffic accidents, vehicle fires etc. occurring in tunnels. Engineering judgement is minimised but is employed where no reliable historical data is available.

System reliabilities are based on historical failure data for similar equipment.

Human consequences are derived from computational fluid dynamics simulations of selected fires and an evacuation analysis in the simulated conditions of heat, smoke and toxic gases. This analysis is not described in detail, only a short description of the methodology that was used is described in the report.

Dangerous goods transport will be prohibited from the tunnel.

A detailed uncertainty analysis has not been undertaken as conservative values are used throughout.

Fire fighting access (personnel or vehicles) has not been analysed in detail, the report does not cover this.

2 Risk Management Process in General

2.1 Introduction

The risk management process is defined differently depending on what kind of risks that are looked at and in what contexts. Before describing the process used for this project the term *risk* should be defined.

The word risk has different meanings to different people, there are health risks, political risks, business risks etc, and there is no precise definition of the term risk. Mattson [1] shows that it is possible to distinguish four different meanings of the word risk depending on the context.

1. Risk means often danger or threat like if someone should say: "There is a risk for cancer by smoking cigarettes".
2. On the other hand if someone says: "By smoking cigarettes, risk for cancer increases". Here is the risk being referred to increased probabilities.
3. Risk is also defined as the balance of frequency and consequences for a certain event.
4. Risk is also being used to describe the degree of variation. A describing example would be the following: Two different companies, A and B, sell a certain product. Company A is expecting to sell between 100 and 200 units per month with an expected value of 150. Company B is expecting to sell between 140 and 160 units per month with the same expected value as company A. It is logical to say that company A is subjected to a higher risk than company B even if their expected values are the same. The risk increases with a larger variation in outcome.

For this project, the term risk is defined as the combination of the frequency with which a hazard manifests itself and the consequences of the manifestation (number 3 above).

The risk management process used for this project is basically the same process defined by the International Electrotechnical Commission, IEC [2]. The risk management process is considered to be divided into three steps:

1. Risk Identification
2. Risk Evaluation/Analysis
3. Risk Reduction/Control

The process is shown diagrammatically on Figure 1 on the following page.

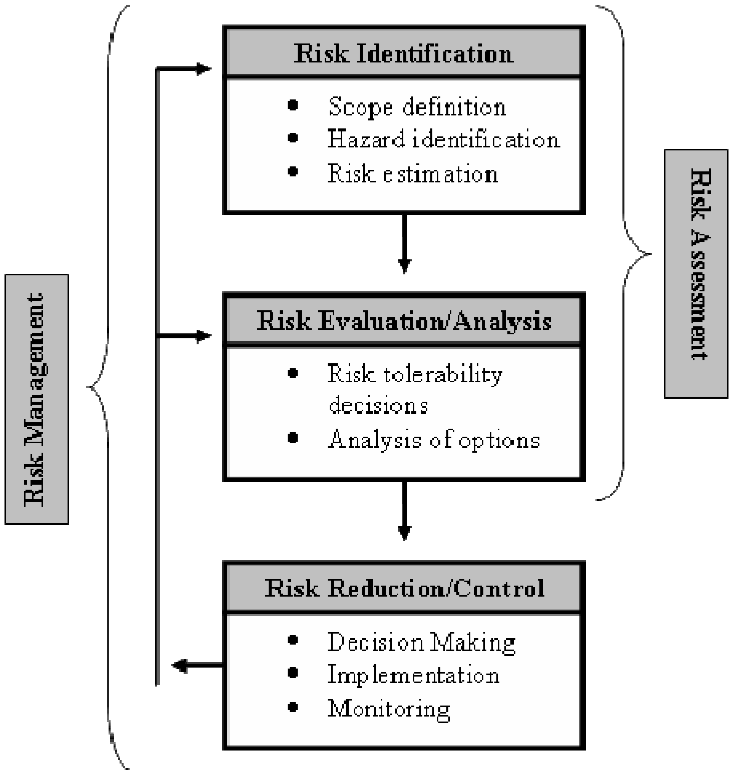

Figure 1 **Risk Management Process.**

2.2 Risk Identification

Risk identification is undertaken by skilled engineers and analysts who have experience of similar environments and the compilation of tunnel fire risk registers. This process is supplemented by brainstorming and 'what if' workshops taking into account the tunnel design.

The hazards are logged and recorded on a Hazard Log (which is often a spreadsheet).

2.3 Risk Evaluation and Analysis

There are a number of different risk analysis methods available. The different methods vary greatly in complexity and are normally divided into three groups.

2.3.1 Qualitative

These methods are more straightforward and they are used early in the risk analysis. The main purpose is to screen out risks that need no further evaluation. Normally non numerical values are used for these methods. Usually some sort of ranking system is used to determine the relevant risk levels for different risk sources. On this level the analysis would normally include a discussion of the methodology, a presentation and discussion of the results.

Typical methods are Preliminary Hazard Analysis and Hazard and Operability Studies (HAZOPs).

2.3.2 Semi Quantitative

These methods are a little more complex than the qualitative ones but they are relatively inexpensive in resources. It demonstrates that all the risks have been considered and enables them to be categorised.

Both the frequencies and the consequences are scored according to simple tables. The bands in the tables tend to be increase in order of magnitude jumps, for example 1 fatality, 10 fatalities, and 100 fatalities.

Each hazard is scored for frequency and consequences and the scores combined using a matrix to indicate the risk. The risks are categorised according to the following table.

Category	Description	Definition
A	Undesirable	Risk tolerated if risk reduction is not practicable.
B	Tolerable	Risk tolerated subject to confirmation that the risk is As Low As Reasonably Practicable (ALARP)
C	Acceptable	Risk accepted subject to endorsement of the supporting hazard analyses.

Table 1 Categories

The frequency and consequence scores are normally debated and agreed in a workshop, attended by the client's professional staff and the risk analysts. The scores are the distillation of combined professional judgement and do contain some subjectivity.

The Hazard Log is transformed into a Risk Register. This register can be used immediately to identify the higher risks. In some instances, it is straightforward to reduce of eliminate these risks by inspection in the workshop and the risk can immediately be reclassified to 'Tolerable' or 'Acceptable'. An example would be the substitution of a toxic product by a non-toxic product of equal efficacy.

The Risk Register is also useful to help decide which, if any, risks need to be fully quantified. For example, it would be unusual to spend scarce resources to fully quantify a risk which had been agreed to be 'Acceptable'.

The Semi Quantitative methodology used in this study is explained in more detail in section 4 of this report and Appendix B.

2.3.3 Fully Quantitative

A quantitative analysis is more objective than the two former ones. The analysis is more detailed and therefore requires more time and resources. Numerical values are always used. Frequencies and consequences are derived from historical records and detailed mathematical modelling. Fault and Event Tree modelling is often used to evaluate the risks.

Objective risk criteria can be implemented to see if the risk is acceptable/not acceptable etc. For a quantitative analysis it is quite normal to include some form of uncertainty analysis. The most common technique is Quantitative Risk Analysis (QRA).

2.3.4 Risk Measures

When evaluating the risks the way in which a risk is expressed/presented is important. There are many different ways of presenting risks.

Life safety risks are normally presented in two ways:

- Individual risk and Societal risk

These are common risk measures to be used in risk analyses. It is important to understand the difference between them and the ways they can be expressed. They are two different measures and they cannot be compared with each other.

Individual risk:

The purpose of the individual risk is to ensure that individuals in the society are not exposed to unacceptably high risks. It can be defined as the risk to any occupant on the scene for the event/hazard scenario i.e. it is the risk to an individual and not to a group of people.

There are several different ways of measuring individual risk; the type to be used strongly depends on the type of hazard scenarios used in the analysis. Quite often it is defined as the likelihood or probability of being killed during a certain exposure time but there are many other definitions, for example in this analysis (traffic) it is presented as fatality per vehicle km.

Societal risk:

Societal risk is not looking at one individual but is concerned with the risk of multiple fatalities. People are treated as a group, there are no considerations taken to the individuals within the group i.e. the definition of the risk is from a societal point of view.

As for the individual risk there are several different ways of expressing societal risk. The most common way to present the societal risk is with an FN curve (Frequency Number curves). FN curves show the relationship between the accumulated Frequency for N or more affected (could be fatalities, injured, etc.), the curve answers the following question "What is the likelihood of being worse than this?" i.e. the frequency of exceedance of a certain value of N. Another quite common way in which the societal risk could be presented is by condensing the information on the FN curve into one number, the average societal risk (it is basically the sum of the probabilities and consequences for the different scenarios).

It is normally necessary to have some kind of risk criteria when evaluating the risk. The criteria can be derived from historical data or already existing national/international criteria can be used.

2.4 Risk elimination/reduction/control

As noted above, it is sometimes straightforward to reduce a risk by the introduction a simple mitigation, which can be accepted by inspection during the semi-quantitative analysis without any formal quantification or cost estimation.

However, there are often occasions where this judgement is not sufficient and so it is essential to fully quantify the risk, with and without the mitigation. Additionally, it is required to estimate the cost of the mitigation, both in capital and operating cost.

Using Cost Benefit Analysis, the costs can be compared to the benefits. Traditionally, this is by calculating the statistical lives saved by the mitigation and comparing it to the value of preventing the same number of fatalities. Some organisations/national bodies publish the value of preventing a fatality but many do not. However, enough do to allow a reasonable value to be used in Western Europe.

If the cost of the mitigation is disproportionately higher than the statistical fatalities prevented, the funds may well be better spent on more worthwhile causes.

3 System Descriptions

3.1 Tunnel Layout

The tunnel systems basically consists of two tunnels that are parallel to each other (the interior tunnel and the exterior tunnel), they are both one-directional tunnels but connections exist between them. They have been divided into segments; the division is based on the layout of the tunnel.

The segments in question are shown in the table below.

Segment	Approximate Length (m)	Description	Width
1	2500	Straight tunnel until large intersection point at north end	4 lanes in each direction
2	1000	Curved tunnel with many ramps at one intersection point.	Majority is 3 lanes in each direction but with single lane ramps and some sections of 5 lanes
3	1300	Gently curved tunnel with occasional ramps. South section is partly open air.	Majority is 5 lanes.
4	1500	Sharply curving tunnels at north end with north section partly in open air. Intersection at mid point.	Majority of tunnel and ramps are 3 lanes.
5	1500	Gently curving tunnels with intersection at mid point.	Majority is 4 lane in each direction with some 3 lane sections

Table 2 Segments / Tunnel layout

3.2 Tunnel Structure

The width of the tunnel sections is naturally determined by the number of lanes. Each lane is 3.5 m wide. A typical 4 lane section has an 18.5 m width between structural walls, being 4 @3.5 plus a 2 m zone at ether side. This 2 m zone is a 0.75 margin plus a 1.0 m pavement plus a drained cavity of 0.25 m.

The main walls will be diaphragm concrete walls or similar about 1 m thick with a 0.8 m concrete base slab propping the walls apart. The base slab is arched downwards to help resist the ground pressures. The height of the tunnel from the roadway to false ceiling is approximately 6 m with another 1 metre of service void or so to the top structural slab.

Drains and other services are contained in the space between the road way and the base slab.

Escape stairs are positioned at approximately 150 - 200 m centres, the spacing varies to suit the ground level positions.

3.3 Ventilation and Smoke Extract Systems

The ventilation system for the tunnel is a mixture of longitudinal and transverse ventilation.

The tunnel is divided into ventilation sections of 600m. For normal mode operation, fresh air is blown into the tunnel at the beginning of the section, the air is moved longitudinally along the tunnel by the vehicles themselves and assisted, if necessary, by jet fans attached to the tunnel roof and positioned at approximately 100 m centres. At the end of the 600 m section, the air is extracted. The ventilation plant rooms are located on mezzanine slabs above the traffic every 600 m. The fresh air is drawn from street level and expelled back to street level.

The main supply and extract fans and the jet fans are ramped up when the environmental monitors detect high levels of carbon monoxide and/or nitrous oxide, or poor visibility.

Additional smoke extract fans are located every 100 m in the tunnel roof. In fire mode, these five sets of fans start to operate within the 600m section, in addition to these five fans the two fans at the beginning/end of the section also go into fire mode (extraction of smoke). Make up air is taken from the two ends of the 600m section.

Control of the longitudinal air velocity in the section is important. If the velocity is too high (>2 m/s) the smoke will mix over the whole cross section downwind of the fire i.e. create untenable evacuation conditions.

The stratification of the smoke layer is very important (to be able to keep a smoke free zone for the evacuation). Longitudinal air velocity should be kept to a minimum consistent with smoke extract.

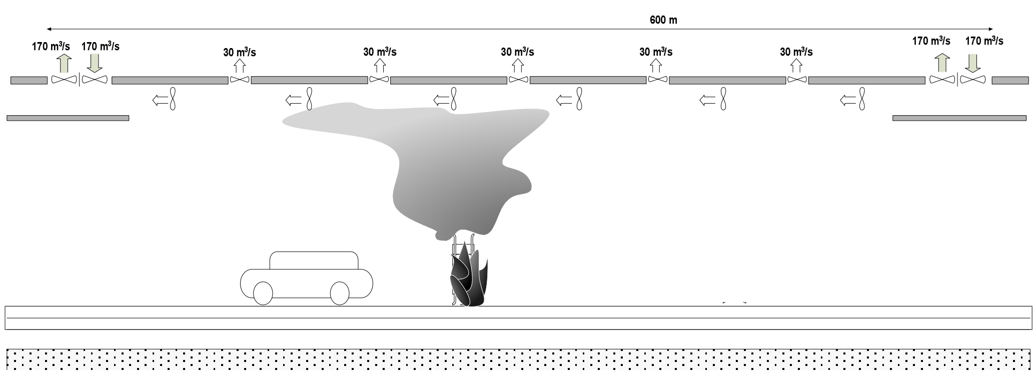

Figure 2 **Ventilation system schematic**

3.4 Fire Detection Systems

The different safety/protection systems assumed for the tunnel have been based upon knowledge of the systems and their use in previous similar projects.

3.4.1 Detection system

The detection system is vital when it comes to tunnel safety. Many of the other systems used in the tunnel depend on the detection system for their operation (ventilation system, evacuation systems, traffic management systems, etc.).

Under normal ventilation conditions, up to 3m/s, hot gasses and smoke rise to the tunnel ceiling within a short time period and can be detected very quickly and reliably, 'Tunnel Fire Safety' [3]. The speed of the detection system decreases with the longitudinal air velocity in the tunnel, it is therefore important that the longitudinal air velocity is kept low. It is shown that the most reliable detection systems for tunnels are heat activated.

The ambient conditions within a tunnel do not suite detection systems normally used in buildings. For example, optical system, smoke detection system, etc.

It is assumed that a "line-type heat-detection cable with semiconductor temperature sensors (multi-point system)" will be most suitable. It is anticipated that two independent line detectors will be installed above the inner and outer lanes to assist reliability and speed of detection. These systems activate an alarm upon a pre-programmed rate-of-rise and a maximum temperature principle. With this type of system it is normally possible to pin point the location of the fire to a few tens of metres.

High reliability can be anticipated for the assumed detection system, the coating of the cable protects against aggressive ambient and mechanical influence. The EN 54 standard [4] should be used when designing the system.

This type of system should be able to fulfil the following requirements:

- Detection cable length of 2000m.
- 30-60 s detection times.
- Guaranteed operation in case of cable breakage by fail safe functions.
- Monitored integration into a fire alarm system.
- Serial interface for temperature and data interchange to SCADA (Supervisory Control and Data Acquisition) systems.
- A maximum repair time of 30 min (change of affected segment) for mechanically damaged cable (performed by a technician once the lane is closed to traffic).

For further details on these systems see, Chapter 5 of Tunnel Fire Safety [3].

3.5 Fire Fighting Systems

A comparison between different countries has been made to see how recommendations and guidelines differ. The assumptions are based on the comparison and experience from similar projects. The following documents have been used for the study; PIARC [5], Fire Safety Guidelines for Road Tunnels [6] and Fire Safe Design, Road Tunnels [7].

It is considered important that the tunnel operator, fire service and other relevant groups establish a task group to determine the necessary safety equipment provision for the tunnel.

3.5.1 Extinguishers

Portable fire extinguishers are considered essential for first aid fire fighting as rapid intervention is very important. The spacing between extinguishers is normally between 50 up to 150m. A spacing of 75m is assumed.

It is assumed that the portable extinguishers are alarmed. If an extinguisher is removed from its support, an alarm signal will be sent to the control room. This alarm serves two purposes, as an extra measure to detect fires and signalling the potential theft of an extinguisher.

3.5.2 Hose reels

Hose reels form part of the first aid fire fighting equipment. Hose reels enable tunnel users to intervene at an early stage of a fire. It is assumed that hose reels will be installed and be placed together with the extinguishers at 75m spacing. As with the extinguishers, the hose reels should be alarmed, i.e. the usage of a hose reel should send an alarm to the control room.

3.5.3 Fire hydrants

A hydrant system has been assumed at a spacing of 150m. The spacing between hydrants normally varies from 85 up to 200m. Hydrants will not be used for first aid fire fighting; they are for fire service use.

3.5.4 Possible Suppression Systems

Suppression systems will be installed in specific parts of the tunnel. This report does not go into detail about this specific analysis but the general view on suppression systems and the main conclusions are given in this and the following section.

In Europe, the general view is that suppression systems should not be used in tunnels, the main concerns is that it will affect the evacuation conditions in a negative way. However, Japan and Australia are in favour of suppression systems and the systems are considered to increase safety.

There are many factors that must be taken into consideration before deciding on if a suppression system should be installed. The main question that needs to be answered is: What is the reason for installing the system? There are different answers to this question depending on what the system is designed to protect. Is the system installed for life safety reasons i.e. to protect the tunnel users? Is property protection and business continuity the reason i.e. is the system there to protect the tunnel structure and prevent down time of the tunnel (tunnel closed due to repair work)?

Once the purpose of the system has been decided there are other factors that influence the decision. What kind of ventilation system is used (transverse, longitudinal, etc)? What is the length of the tunnel? What kind of traffic is to be expected? How are the emergency exits distributed? etc. When these factors has been taken into consideration and the decision is to incorporate a suppression system the question is to decide what type of system that should be used. There are many different systems on the market (foam water sprinklers, water spray systems, water mist systems, etc.). The performance of the system depends a great deal on what kind of nozzles that are used and the system layout. The types of system considered for the tunnels are water spray and water mist.

3.5.4.1 Water spray / water mist

These two systems have quite different systems characteristics. The water spray system works at much lower pressure, the discharge density is much higher and the droplet size is bigger. It is considered that water spray systems have a bigger effect on the fire i.e. controlling the fire in a better way than a water mist system. The water spray systems require a significantly larger amount of water in comparison to the water mist system.

Normally the installation cost of a water mist system is more expensive than for a water spray system.

For property protection, business continuity and fire fighting purposes it is considered that a suppression system would be very advantageous in the case of a heavy vehicle fire, for fires smaller than this the benefits of the system would be lower (this is due to the fact that smaller fires are not considered to have a big impact on the tunnel structure).

It has been assumed that the suppression system is manually activated and only once the evacuation from the tunnel is largely completed. Early automatic activation is discouraged but it should be possible to effect a default time in case the operator is incapacitated. The system should have the capacity to function for at least 60 minutes. The water spray system would require about 4-5 times more water than the mist system.

Both types of suppression systems are considered to be able to protect the tunnel structure and improve conditions for fire fighting; from this point of view both systems are acceptable. The water spray system is considered to be able to control the fire better than the water mist system; this may affect the fire fighting conditions in a better way.

Both systems are considered to be acceptable and the decision to use one or the other should be based on practicality of installation and cost implications.

3.6 Electrical Power supply

The power supply system for the tunnel is vital. Basically all systems used in the tunnel are dependent on the power supply.

A reliable power supply with multiple redundancies and back-up systems is assumed. The customary installation includes two independent high voltage supplies feeding two independent transformer sets. The low voltage supplies then feed half the load each but are capable of feeding the total load via an automatic transfer switch which activates on the loss of one supply. Back up diesel generators are included in many, but not all, installations.

Uninterruptible power supplies are normally provided to power essential control equipment.

The main feeders are located where they will not be liable to mechanical impact of fire. When infrastructure protection cannot be provided the use of fire rated cables should be considered.

3.7 Communication Systems

A comparison between different countries has been made to see to how recommendations and guidelines differ. The assumptions are based on the comparison and experience from similar projects. It is considered important that the tunnel operator, fire service and other relevant groups establish a task group to determine the necessary safety equipment provision for the tunnel.

3.7.1 Emergency telephones

Emergency telephones are normally provided in road tunnels. The distance requirement between emergency phones varies from 50m up to 500m. The emergency phones basically serve for reporting accidents in tunnels and as back up system, redundancy is necessary in order to achieve a high probability of the appropriate action to an emergency. Alarm push buttons form part of the manual detection system, as do the emergency phones.

It is assumed that the tunnel is equipped with the emergency phones, due to the other systems that are assumed for the tunnel is considered sufficient with a distance of 300m between them.

3.7.2 Manual accident/fire alarm

Alarm push buttons are normally considered optional for tunnels. They form part of the manual alarm system (accidents and fires). It is considered that the alarm push buttons form an important part of the manual alarm system. The tunnel is assumed to be fitted with manual push buttons and they should be placed at all emergency exits and together with the extinguishers/hose reels i.e. a maximum distance of 75m between them.

3.7.3 CCTV

CCTV is a very useful tool for monitoring traffic and even more important when it comes to unwanted events such as traffic accidents and fires. Tunnels with high traffic densities and tunnels that are manned are normally equipped with CCTV. The spacing requirement varies between 100 and 300m. It is assumed that CCTV is installed in the tunnel. The installation should cover the whole tunnel length. The CCTV permits rapid detection and verification of accidents, especially fires, this gives the tunnel operator an advantage when it comes to take the necessary decisions (actions to mitigate the consequences). The spacing between cameras should not exceed 150m (this also depends on the performance of the CCTV system). CCTV with IR capabilities (for fire detection) has been investigated but this system is not considered to have any significant additional benefit.

3.7.4 Emergency signage

Emergency signage is a very important safety feature for a tunnel. All exits are assumed to be equipped with lighted exits signs. The tunnel is assumed to be equipped with at least two directional signs between two exits, the directional signs should show the distance to each exit and it should be lighted. To make it easier for people to find and choose an exit the exit signs should be equipped with green strobe/flashing lights. Research, Human behaviour in tunnel fires [5], shows that the decision making time will probably be reduced and people will start the evacuation earlier, which is very important for tunnels.

The traffic signage (electrical information panels) could be used to inform tunnel users of emergency situations. This could be especially helpful in situations when evacuation from the tunnel is necessary.

3.7.5 Voice Alarm System

There is quite a big difference in the use of VA systems (Voice Alarm system, loudspeakers) for tunnels, in some countries they are required, in some optional and in some even not recommended. Recent research has shown that a VA system could be very important for the evacuation of a tunnel. Especially for tunnels it is important that the evacuation is started as early as possible, persons that are informed (via the VA system) at an early stage will reduce the decision making time and start their evacuation earlier.

The provision of a VA system could meet the following problems:

- Communications is normally only possible in tunnels with acoustic treatment.
- The noise from vehicles and fans can be a problem.

These problems should be solved so that an incorporation of a VA system is possible. It is assumed that a VA system is used. It is important that it is combined with proper tunnel management procedures.

3.7.6 Radio communication

Emergency and operation services need to be able to communicate with each other and with the tunnel control. Commercial radio rebroadcast could be of advantage because it gives the opportunity to pass on safety messages to the public i.e. the tunnel users. Normally the decision to install radio communication facilities depends on the complexity of the tunnel (length, traffic densities, etc). The length requirement to install these facilities varies between 800 to 10,000 m.

It is assumed that emergency services radio rebroadcast facilities are provided for the tunnel. Commercial radio rebroadcast facilities should be considered, this could be used to inform/alert the tunnel users during tunnel emergencies (safety messages, RDS radio broadcasting etc).

3.8 Means of Escape

Escape stairs to the surface have been included approximately every 100 to 200 m. At present the stairs are the main means of ingress for the emergency services and egress for the evacuating tunnel users. As far as the author is aware, the emergency services and the tunnel users will use the same single stairs so there is potential for conflict.

4 Semi-Quantitative - Risk analysis

4.1 Broad Evaluation of Risks, Segment by Segment

The characteristics of the different tunnel segments vary considerably. A simple semi quantitative analysis has been performed to try to establish if the accident frequency will vary among the different segments. For most segments both the interior tunnel and the exterior tunnel have been looked at, when this is not the case the tunnel layouts were very similar. For segments 2 and 3 it was considered to look at these segments as one due to their similarities (but divided into interior and exterior). For details of the segments see section 3.1 of this report.

The following table shows the segments that have been considered.

Segments	Tunnel
1	Interior and Exterior
2/3	Interior
2/3	Exterior
4	Interior
4	Exterior
5	Interior
5	Exterior

Table 3 Segments

The analysis has to some extent used public statistics but it is also based on engineering judgment. It was decided to look at four different factors; these factors are considered to have an effect on the accident frequency.

The four factors are as follows:

4.1.1 Slope (degree and variation)

The slope of the roadway is assumed to affect the number of accidents. The vision is assumed to be affected and could result in rear end collisions (late breaking). It is also assumed the slope will affect the motor heating and break heating (the clutch and brake system could be especially affected in congested traffic); in the PIARC document [5] it is mentioned that the slope will affect the motor and break systems.

4.1.2 On/Off ramps (numbers and location)

The existence of converging and diverging lanes is assumed to have a significant effect on the number of accidents. Especially diverging lanes require the users of the route to make a decision and take actions that could affect other users. It was noted from accident statistics [9] that road sections with a higher amount of converging and diverging lanes had a higher accident rate. The same statistics also show that many accidents occur in the vicinity of exits (Off ramps).

4.1.3 Length of section

It is assumed that the number of accidents on any road is proportional to the length of roadway. The PIARC document [5] shows that the number of accidents is directly proportional to the total vehicle km per year experienced by a tunnel.

4.1.4 Curvature of section

It is assumed that straight sections are less prone to cause accidents than sections with curves. It is considered that the lack of clear vision ahead and the direction change of lanes could affect the accident rate.

The internal importance weightings of the factors have been derived on basis of statistical data where available, complimented by engineering judgement. It is concluded that the most important factor is the On/Off ramps followed by the slope factor. The two remaining factors, length and curvature, are considered to be of similar importance but less important than the two former ones.

The following table shows the importance weighting given to the different factors.

Factor	Importance
On/Off ramps (number and location)	0.500
Slope (degree and variation)	0.300
Length of section	0.110
Curvature of section	0.090
Sum	**1.000**

Table 4 Internal importance

The different sections were examined having the different factors in mind. Each section was scored on the factor. A grading from 1 to 4 was used, 1 being the safest and 4 being the most risky. The results from this process are shown in Appendix A.

4.1.5 Results

The summary results can be seen in the following table, the calculations are included in Appendix A.

Ranking			
Risk Rank	**Segment**	**Tunnel**	**Relative risk**
1	2 / 3	Interior	3.26
2	2 / 3	Exterior	3.01
3	5	Interior	2.25
4	4	Exterior	2.08
5	4	Interior	1.74
6	1	Exterior and Interior	1.61
7	5	Exterior	1.00

Table 5 Risk Rank Summary

As can be seen from the summary table above there are differences between the different segments of the tunnel. The analysis suggests that the segment 2/3 (interior and exterior) will have a higher accident frequency. This result can be used to determine where more proactive measures should be used.

Although there is a difference between the sections, the difference is not an order of magnitude and it is based on a simple analysis so the segments are all treated the same for the semi-quantified risk analysis (see next section).

4.2 Semi Quantified Risk Register

4.2.1 Explanation

The risk register is contained in Appendix C. It is compiled using the methodology described below and in Appendix B.

All segments have been taken to manifest equal risk for this semi-quantified analysis, as explained in Section 4.1 above.

The hazards are considered to be light and heavy vehicles. Light vehicles are cars, vans and small busses. Heavy vehicles are trucks and large busses. No dangerous goods will be permitted so vehicles carrying large quantities of hydrocarbon fuels are excluded.

Congested and non congestion traffic are treated separately as any impact speed will be markedly slower for congested conditions but the probability of the initial fire spreading will be greater and the number of people who have to evacuate will be greater.

The Frequencies are scored according to the Frequency Table in Appendix B.

The Consequences are based upon the Consequence Table in Appendix B.

The Initial Mitigation column records the safety systems which are installed and operational. Engineering judgement is used at this stage to assume that the fire detection systems will be very reliable but that the smoke extract systems will be less reliable and ought to be considered separately as their reliability will depend on their periodic testing regime and the automatic fan temperature shut off in a fire.

Risks #1 and #2 (road traffics accidents) frequencies are based upon known historical data and are included to benchmark the risk register frequencies. The frequencies of the remaining risks #3 to #18 are based upon engineering judgement.

For simplicity, it has been taken that congestion will occur for 25% of the time, say 6 hours per day.

It is judged that the smoke extract system will be at least 90 % reliable.

The consequence score is derived from the Consequence Table.

The risk is automatically calculated from the Risk Matrix in Appendix B.

The penultimate column allows for any mitigation measures which can be made by inspection.

The final column shows how the analysis has helped to select the fire modelling scenarios.

4.2.2 Results

The table below summarises the risks before and after the mitigations measures.

Category	Description	Original	With Mitigations
A	Undesirable	1	0
B	Tolerable	12	8
C	Acceptable	5	10
Total		18	18

Table 6 Risk Categories

The original analysis indicated only one ‘Undesirable‘ risk (#1) associated with road traffic accidents where there was no resultant fire.

Twelve (12) ‘Tolerable’ risks were estimated ranging from relatively common small cars fires to much less frequent, but very serious, multiple HV fires.

There is little more that can be done physically to reduce the everyday road traffic accidents without fires at the segments under consideration as it is assumed they are being designed to the latest layout standards. However, strict control of vehicle speed and prosecution of offenders will restrict the number of accidents.

5 Fully Quantitative Risk Analysis

5.1 Process

The methodology used for the fully quantified risk analysis is described with the following steps:

1. Input from qualitative analysis

In the qualitative/semi-quantitative analysis different accident scenarios were identified. These scenarios form a base for the construction of event trees and the development of fire scenarios to be used in the consequence modelling.

2. Event tree analysis

Event trees are constructed. These show the different scenarios that need to be considered for the analysis. The probabilities and frequencies used for the event trees are determined as well.

3. Consequence modelling

Based on the scenarios (outcome) from the event trees different fire scenarios are determined, the event trees are still not completed. These fire scenarios are modelled and the results are used in conjunction with an evacuation analysis; this will give the consequence figures for the different scenarios.

4. Evaluation of results

The consequence modelling results are used as input for the event trees. The now completed event trees are used to determine the individual and societal risk. Benchmarks are developed and used for the comparison of the risks.

5.2 Methodology

5.2.1 Event Trees

The fully quantitative analysis employs Event Trees as the basic tool to estimate the frequencies of the scenarios considered. An event tree starts with an initial event and the purpose is to find the frequencies/probabilities for different outcomes (based on the initial event).

Event trees are used to predict the frequencies/probabilities of infrequent events by the logical connection of a series of much more frequent sub events for which data is available. Event trees work forward from an initiating event to generate branches defining events and paths resulting from secondary (or nodal events) to investigate the range of outcomes. The frequency associated with each branch (outcome) is given by multiplying the initiating frequency with the relevant conditional probabilities of success/failure.

The following figure shows a section from one of the event trees used in the analysis (with fictive figures), the initial event is fire in a vehicle. As can be seen from this specific three there are three different end scenarios (outcomes).

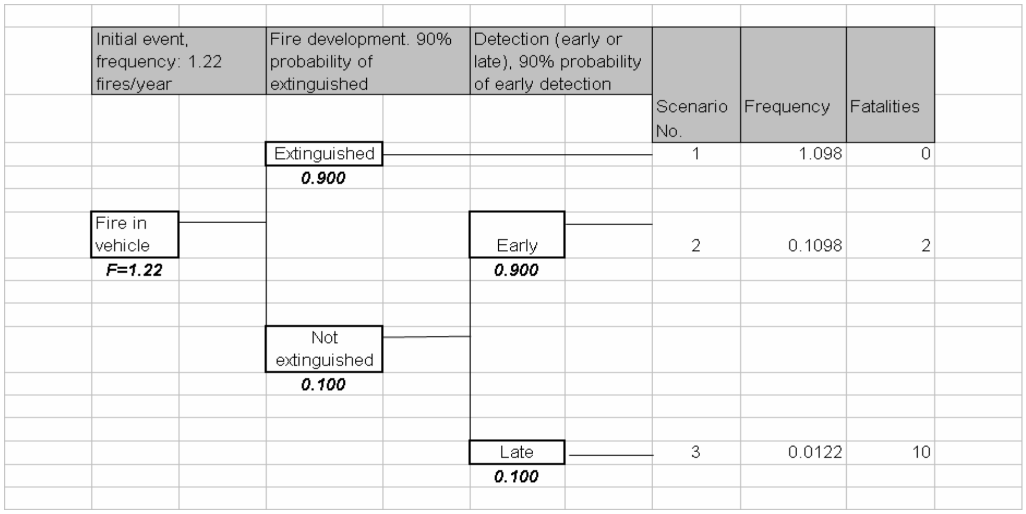

Figure 3 **Event tree**

5.2.2 Fault Trees

The Fault Tree Analysis is used to calculate the frequency/probability of failure for a certain event (top event) and to gain knowledge about which events that are causing the failure to occur. A fault tree is a graphical representation of logical relations between an undesirable top event and primary cause events.

The construction of a fault tree starts with the definition of the top event. The tree is constructed by placing various cause events in correct sequential order. This is normally done by working backwards from the top event and specifying the events causes, faults or conditions that could lead to the occurrence of the top event. This process is continued and terminated when a final set of base events, faults or conditions are identified. Probabilities/frequencies are then assigned to the base events.

The events in a fault tree are connected by logic gates that show what combination of the constituent events could cause the particular top event. These logic gates are mainly AND gates in which all the constituent events have to occur and OR gates in which only one of the constituent events need to occur to cause the occurrence of the top event.

A typical fault tree is shown below. Here the top event is “Emergency sounder not working”. The causes of this top event can be followed through the different cause events.

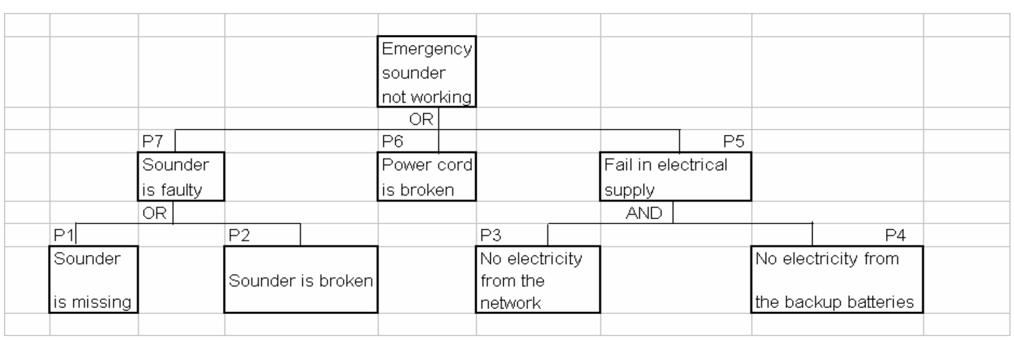

Figure 4 **Fault tree**

5.3 Event Tree Description

The Event Trees are contained in Appendix E.

From the semi quantitative analysis different accident scenarios (hazard events) were derived. The ones used as a base for the construction of the event trees and the developments of fire scenarios are shown below:

- Single Light Vehicle fire (2.5–5 MW)
- Multiple Light Vehicle fire (7 MW, 2-3 small cars or 1 large car)
- Single Heavy Vehicle fire (30-70 MW)
- Multiple Heavy Vehicle fire (70 MW)

5.3.1 Initial Frequencies (Column 1)

The first column of the event tree shows the expected annual frequency of a small fire in a vehicle.

Frequencies used for this analysis is mainly based on a French tunnel study [5] and data about fires in a number of different tunnels [5], both urban and rural.

The table below shows the figures used for the analysis. Appendix D shows the detailed analysis to establish the initial frequencies.

Vehicle type	Traffic mode	Frequency (fires per year)
Heavy vehicle	Not congested	2.0
Heavy vehicle	Congested	0.7
Light vehicle	Not congested	4.4
Light vehicle	Congested	1.5

Table 7 Frequencies

The probabilities used in the analysis (mainly used for fault trees and event trees) are mostly based on historical data. Engineering judgement is minimised but used to some extent when no reliable historical data is available. A detailed description of all the probabilities used can be found in Appendix D.

5.3.2 Fire Development (Column 2)

Column 2 considers if the small fire is extinguished locally. If it is, the fire is not considered further and the event tree branch remains a single line.

Fault trees have been used to calculate reliability figures for the detection and ventilation systems. The results obtained from the fault trees have been used to develop the event trees.

5.3.3 Fire Detection (Column 3)

Column 3 considers the early or late detection of the fire. Fault Tree Analysis has been used to calculate the probability of early detection at 99%.

The detailed analysis of the fault tree can be seen in Appendix D.

5.3.4 Ventilation and Smoke Extract (Column 4)

Column 4 takes into account the probability that the ventilation and smoke extract systems operate as intended. Again Fault Tree Analysis has been used to estimate they will start on demand 90% of the time.

The detailed analysis of the fault tree can be seen in Appendix D.

5.3.5 Fire Suppression (Column 5)

Column 5 then considers the probability that the suppression systems will function. Clearly the probability is zero if no suppression system is involved.

The detailed analysis of the fault tree can be seen in Appendix D.

5.3.6 Frequencies (Columns 6 and 7)

Column 6 calculates the annual expected frequency of each branch using the initial frequencies and the relevant probabilities and column 7 transforms this frequency into a rate per 100 million kilometres.

5.4 Consequence modelling (Column 8)

A detailed description of the consequence modelling does not form part of this report. However, a general description is given in the sections below.

5.4.1 General

Another important part of a risk analysis is to determine the consequences. Consequences in a risk analysis can be given in many different units; fatalities, injured, loss of money etc. The unit used depends on what type of risk analysis that is being conducted and the complexity of the analysis.

For risk analyses concerned with life safety it is normal to use a computational model that measures physical effects on humans and in that way calculate the consequences for different scenarios.

5.4.2 Fire Modelling Scenarios

The different fire scenarios developed are based on the event trees and the accident scenarios derived from the semi quantitative analysis.

All the different end scenarios derived from the event trees can not be modelled. It is however quite important that the fire scenarios developed represents a wide range of the end scenarios. In this way the consequence figures for the end scenarios not modelled can be estimated.

The scenarios modelled are described in more detail later on in the report.

5.4.3 Fire Modelling

The fire modelling is done with a Computational Fluid Dynamics (CFD) program; the program is called Fire Dynamics Simulator (FDS).

FDS is a software package developed by the national Institute of Standards and Technology (NIST) of the USA. The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. Version 4.05 of FDS has been used. The program is widely used and the model has undergone a considerable amount of validation work.

The usage of CFD codes are widely used as a basis for simulating fires in tunnels. They facilitate the rapid development of simulations and embody many of the physical models that are needed for such simulations, for example turbulence models, buoyancy source terms, combustion and radiation models.

In a simplified way it can be said that the program models a fire within the geometry used (in this case a section of the tunnel). The smoke production and smoke spread along the tunnel is calculated, it is also possible to calculate the visibility, temperature, amount of toxic gases, radiation etc for different areas at different times along the tunnel. In this way it is possible to determine in which areas untenable conditions occur and even more important when they occur.

5.4.4 Evacuation Modelling

A simple evacuation model has been used for the evacuation modelling. The model is based on hand calculations and pre determined pre movement times.

For the evacuation process, the process can be defined as the time when people start their evacuation until they are in a place of safety, can be divided into various parts. Each part is analysed and different times are assigned to them. The evacuation process can be considered to be divided into the following parts:

- Pre movement time

  This time can be considered to consist of awareness time and reaction time. The awareness time is the it takes for an individual to become aware of the threat, the reaction is time it takes for an individual to decide to start the evacuation once he has become aware of the threat.

- Movement time

  This is the time taken for the individual from that he has physically started the evacuation and until he is in a place of safety. It can be considered to consist of walking time and queuing time.

The goal with the evacuation modelling is to determine the required evacuation times for the tunnel users and compare this with the time to reach untenable conditions. In this way the consequences for different fire scenarios can be calculated.

For the modelling different detection times were used; 1 minute was used when the detection system was considered to work normally (a realistic assumption), 4 minutes was used if the detection system not was considered to work normally (this is considered to be a conservative assumption).

5.4.5 Scenarios Modelled

The eight scenarios are shown in the following table.

Run	Scenario
1	7 MW + ventilation (early activation of ventilation)
2	30 MW + ventilation (early activation of ventilation)
3	7 MW + partial ventilation (early activation of ventilation)
4	30 MW + partial ventilation (early activation of ventilation)
5	7 MW + ventilation (late activation of ventilation)
6	70 MW + partial ventilation (failure due to heat), (early activation of ventilation)
7	30 MW + ventilation (early activation of ventilation)
8	7 MW + ventilation (early activation of ventilation)

Table 8 Fire/Consequence modelling

Based on the runs shown in the table above the consequence figures for all the different end scenarios were calculated.

5.5 Risk Benchmarks

The development of risk criteria is an important part of the quantitative analysis. The criteria are used to determine or at least to get an idea if the investigated risks are tolerable or not. Generally the risk criteria need to be agreed and accepted between the different interest parties.

It is not part of this study to develop individual and societal risk acceptance criteria for this tunnel project. However, Appendix F develops benchmarks which are used below for comparison to the results from this study.

Risk criteria especially constructed for traffic are not easily obtained, and to find risk criteria specifically related to traffic and fire requires judgement. For this analysis risk criteria (regarding traffic accidents) from Norway and Austria have been used to develop benchmarks for this tunnel. It is important to point out that the risk criteria used in Norway and Austria includes all traffic accidents not only fires. Historical data (road accidents) for the motorway section being replaced by the tunnels has also been used. Appendix F shows how the risk benchmarks for this tunnel were developed.

The benchmarks developed are not directly used to determine if the risks are acceptable or not but more used to see how the fire accidents risks and accidents risk criteria are in proportion to each other. By determining this it is possible to make an assumption about the risk level and in that way decide if the risks are considered tolerable or not.

The following benchmarks are used to evaluate the risks in the tunnel (Appendix F shows how they were developed):

5.5.1 Individual risk

The individual risk benchmark for total fatalities in road tunnels is as follows:

- 0.30 fatalities / 100 million vehicle kilometres

5.5.2 Societal risk

The societal risk benchmarks for total fatalities in road tunnels are shown in the following figures:

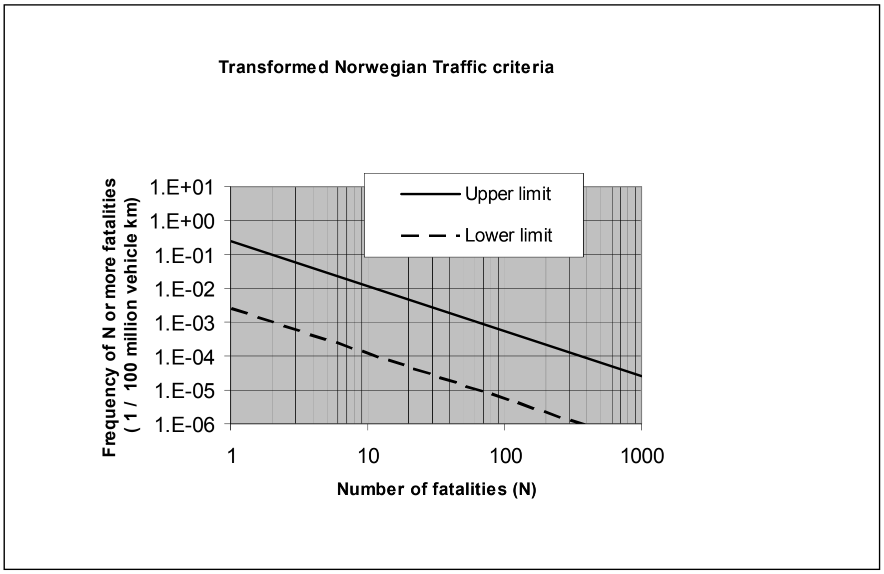

Figure 5 Transformed Norwegian Traffic Criteria

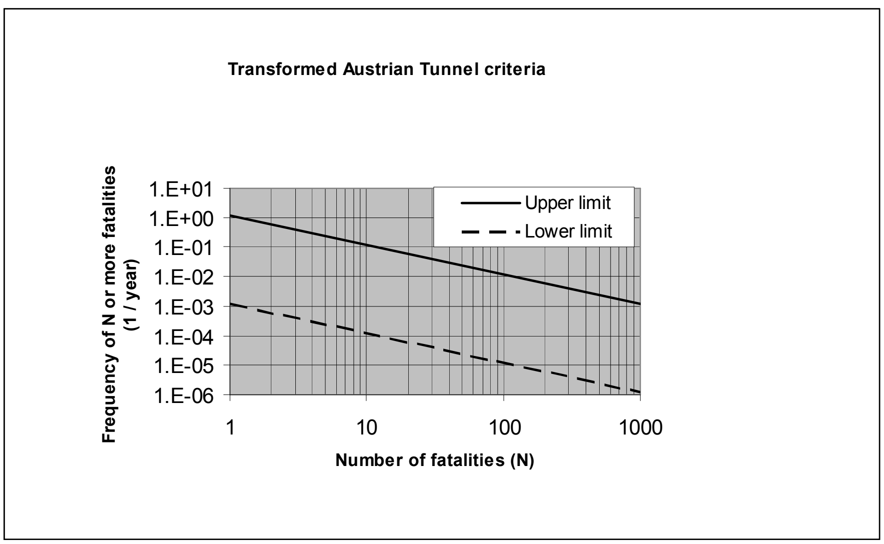

Figure 6 Transformed Austrian criteria

5.6 Risks

5.6.1 Individual Risk

The table below summarises the expected number of fatalities calculated with the event trees, see Appendix E (Event Trees).

Scenario	**Expected number of fatalities per year**	**Percentage of total risk**	**Percentage of traffic**
Heavy vehicle fire	1.52	86%	7%
Light vehicle fire	0.25	14%	93%
Total	1.77	100%	100%
Scenario	**Expected number of fatalities per 100 million vehicle Km**	**Percentage of total risk**	**Percentage of traffic**
Heavy vehicle fire	0.36	86%	7%
Light vehicle fire	0.06	14%	93%
Total	0.42	100%	100%

Table 9 Expected values

The expected number of fatalities for the 6 km section under consideration is approximately 1.8 fire related deaths per year. The anticipated vehicle kilometres are approximately 423 million per year, giving a rate of:

- **0.4 fatalities / 100 million vehicle kilometres**

The table below compares the rate against the Norwegian rate quoted in Section 5.5.1 above (both per 100 million vehicle kilometres)

Tunnels (predicted fire)	**Current Motorway (historical, all accidents)**	**Norwegian Tunnels Fire Benchmark**
0.4	0.5	0.3

Table 10 Individual Risk Benchmarking

It can be seen that the individual fire risk is greater than the Norwegian benchmark tunnel fire rate and approaching the current rate for all road accidents (for this specific part of the motorway).

5.6.2 Societal Risk

The tunnel fire risk is compared to the Norwegian and Austrian Criteria on Figures 7 and 8 below.

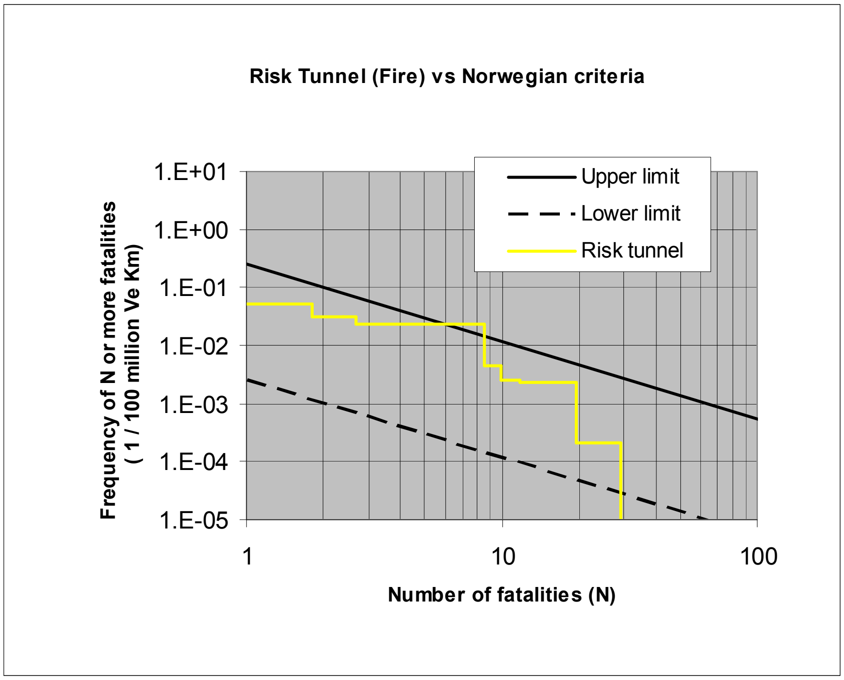

Figure 7 **Norwegian Comparison**

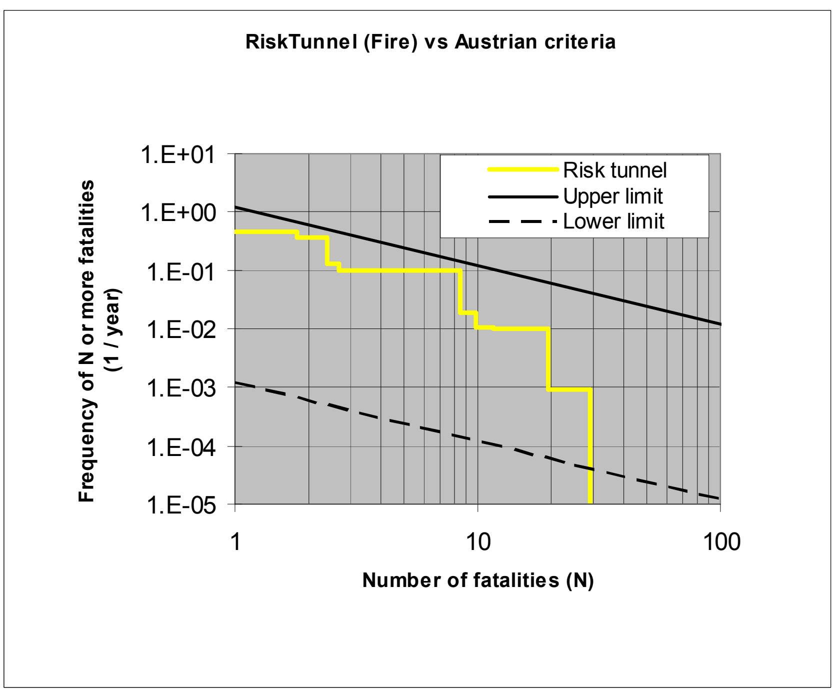

Figure 8 **Austrian Comparison**

The tunnel societal risks effectively fall beneath the Norwegian and Austrian upper criteria for all road tunnel accidents.

However, in the figures above the fire risk is compared with the total risk (all accidents included). Fire risks are traditionally only about a quarter of all road tunnel risks, so the benchmark lines shown should actually be lowered. If this is done the fire risk will be a bit above the benchmark lines, this suggests that further risk mitigation measures need to be considered.

5.7 Conclusions

Both the individual and the societal risks are somewhat greater than the benchmarks for the tunnel in general, remembering that the benchmarks are aspiratory rather than achieved in practice.

For both the analysis there are two significant conservatisms:

- Very fast fire growth rates have been used.
- The fire has been placed in the worst possible position from an escape point of view (blocking a fire exit).

Much of the risk results from passengers queuing at the escape exits. Wider exits would alleviate the problem.

For the tunnel in general the following can be said:

- Fires in both light and heavy vehicles are a tolerable risk.
- Fires in light vehicles in congestion are also tolerable.
- Fires in heavy vehicles during congestion are a concern.

A water suppression system is not considered to have a significant effect on saving human life but mitigates the commercial loss.

5.8 Mitigation Measures

The analysis suggests that the risk for the tunnel is slightly too high and further risk mitigation should be considered.

There are basically two ways of decreasing risks:

- Reduce the probability of the occurrence of the incident
- Reduce the consequences of the event

There are of course many different ways of reducing the risks. As the risk analysis shows the risks from heavy vehicle fires are dominant, the ways of decreasing the risks should be tailored for heavy vehicles. In the following sections some ideas are shown.

5.8.1 Reduce probability of event

- Ban heavy vehicles during known periods of congestion
- Ban heavy vehicles from the tunnel altogether
- Restrict heavy vehicles to the inside lane and prohibit heavy vehicle overtaking
- Install temperature sensors in the tunnel to detect overheating vehicles
- Initiate a public awareness campaign to alert drivers to risks
- Monitoring compliance with traffic regulations especially distances between vehicles and speed of vehicles. Penalties should be given for traffic violations.

5.8.2 Reduce consequences of event

- Increase the capacity of the escape stairs to avoid queuing.
- Test the smoke extract fans at monthly intervals
- Develop an emergency plan
- Initiate a public awareness campaign to educate the drivers in emergency evacuation
- Carry out and publicise evacuation drills
- Consider obliging heavy vehicles to carry fire extinguishers

5.8.3 Risk levels with mitigation measures included

Three of the mitigation measures have been tested to see what effect they have on the risk level.

The three mitigation measures considered are listed below:

- Ban heavy vehicles during known periods of congestion
- Ban heavy vehicles altogether
- Increase width of escape exits

Exit widths are increased to 2500mm. The maximum queuing time with this exit width is 1.5 minutes (maximum with 1500mm exit is 3 minutes). It is assumed that when the exposure time is reduced by 50% (or more) the consequences (due to queuing) will be reduced by at least 50%.

The table on the following page shows how the risk level was reduced.

	Expected Value (fatalities per year)	Risk Level
Original (no mitigation measures)	1.77	100%
Heavy vehicles not permitted in the tunnel	0.25	14%
Heavy vehicles not permitted during congested hours	0.88	50%
Increased exit widths (2500mm)	1.35	76%
	Expected Value (fatalities per 100 million Ve Km)	**Risk Level**
Original (no mitigation measures)	0.42	100%
Heavy vehicles not permitted in the tunnel	0.05	12%
Heavy vehicles not permitted during congested hours	0.20	48%
Increased exit widths (2500mm)	0.32	76%

Table 13 Risk level

As can be seen in the table all three mitigation measures have a significant impact on the risk level, the heavy vehicles measures are the most effective ones.

6 Tunnel Safety Management System

There are two main approaches when it comes to controlling risks; reactively and proactively. The reactive approach basically consists of implementing measures after an accident. The accident shows what went wrong and measures are implemented to prevent reoccurrence. A proactive approach anticipates what could happen and implements measures before an accident occurs to reduce the probability of an accident occurring and/or to reduce the possible consequences from an accident.

It has become more and more important to think proactively. In a dynamic environment, hazard sources, their control requirements, and sources of disturbances change frequently and risk management can no longer be based on responses to past accidents and incidents, but must be increasingly proactive, Rasmussen [10].

To control risks there is a need for a Safety Management System (SMS), these systems are used widely in the chemical and nuclear industries. It has been shown that the most common reasons for accident can be related to failure in the management and by implementing safety management systems such failures should be reduced.

A tunnel safety management system should be integrated, as early as possible, in the design process of the tunnel. By integrating it at an early stage it enables a more structured and proactive approach towards safety issues. A safety management system should include the following very important points, Kemikontoret [11]:

- Policy
- Routines
- Instructions

The vision and objectives are stated in the policy. Routines are created to give clear and simple information about how work is organized; these routines are based on the policy. Instructions are more detailed and form part of a routine.

The policy for the organisation needs to be clear, it should state the safety goals, and the organisations view of safety should be defined. When implementing a tunnel SMS it is important that it is implemented on all levels of the organisation. It is necessary that the organisation have a plan of how to implement the vision and objectives stated in the policy. This plan should at least include the following areas:

- Responsibilities
- Target dates
- Available resources

A special group that deals with safety issues, and make sure that the different safety projects are followed through etc should be created. This group should consist of a project manager and representatives from all the relevant areas. When implementing the plan it is important that the information reaches all the relevant parts of the organisation. It should be carried out by competent personnel and the necessary resources should be available. The safety management system must also include a review system, it is necessary with both an internal and external review to get a neutral perspective.

A tunnel safety management system can be seen to be dynamic and the aim is to constantly improve the system i.e. increase safety. The following figure shows a typical safety management system cycle.

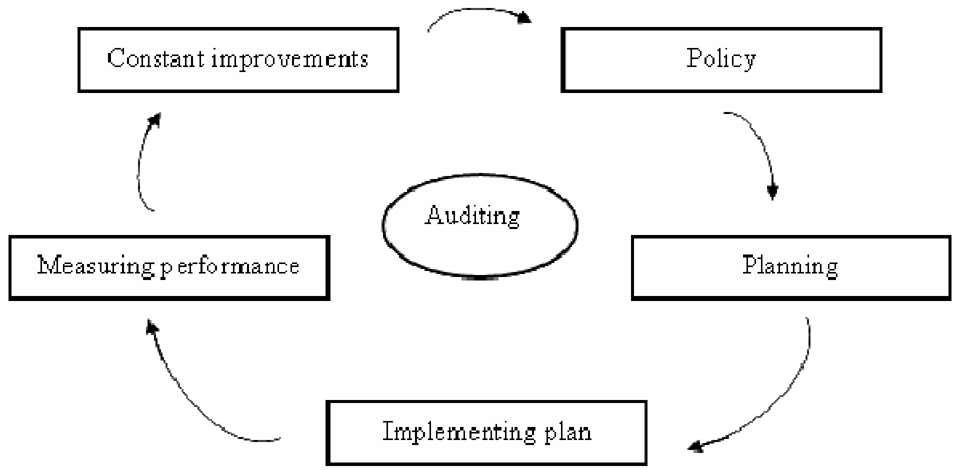

Figure 11 Safety Management System Cycle

There are many advantages of having a safety management system, some of the advantages not mentioned earlier are listed below:

- The system makes it easier to live up to local and international safety rules and standards.
- The credibility of the organisation increases, and it shows that the organisation prioritizes safety issues.
- The effectiveness of dealing with safety issues increases.
- One of the main concerns of the public is safety; a safety management system makes it easier to keep a good relation between the organisation and the public.

6.1 Incident Management Plan

The creation of an Incident Management Plan (emergency procedures and contingency plans) forms an important part of the tunnel Safety Management System (SMS).

It is considered important with the early involvement of the tunnel operator and the fire service and other emergency services in the design of the tunnel and the provision of fire and life safety facilities. This early involvement allows the incorporation of design concepts based on what is considered as best practice from local, national and international standard.

To prepare and document the Incident Management Plan (emergency procedures and contingency plans) is considered vital in preparation for an emergency. It should be prepared by the operators of the tunnel in close collaboration with all the emergency services and the principal users. This representation is best achieved through the establishment of an Emergency Management Committee.

It is important that the plan is clear, concise and as brief as possible. It should identify the roles and responsibilities of all parities in the event of an emergency. The tunnel characteristics may vary in different parts of a tunnel and it is therefore important the emergency procedures and contingency plans reflect this.

7 Conclusions

7.1 Risk Tolerability

The semi quantitative analysis concludes that the risk for the tunnel users is tolerable/acceptable but that further mitigation measures should be considered. A quantified risk assessment (QRA) is required to more accurately identify the risks and assess appropriate mitigation measures. The conclusions from the QRA done for the tunnels are discussed below.

The semi quantitative analysis also suggests that segments 2 and 3 are prone to have more accidents than the other segments due to their characteristics.

The QRA results showed the risk to be tolerable for the parts of the tunnel investigated in this report.

7.2 Benchmarking

A conservative benchmark has been used against which to compare the tunnel risk. In the discussion below it must be borne in mind that this is a level of risk aspired to for the design of road tunnels in Norway and Austria, and not necessarily achieved.

The quantitative analysis shows that the risks are slightly higher than equivalent criteria for all road deaths in tunnels in Norway and Austria.

As fire deaths are expected to constitute only 25% of all road deaths, the fire risk is greater than the benchmark level.

7.3 Conservatisms

The analysis is acknowledged to be conservative, mostly from the facts that a very high fire growth rates which have been used in the analysis and the fire has been positioned so as to block an escape stair.

7.4 Congestion

Fires in both light and heavy vehicles present an acceptable human risk when there is no congestion.

Fires in light vehicles in congestion are also tolerable.

Fires in heavy vehicles during congestion are barely tolerable and further mitigation should be considered. A high proportion of the risk results from passengers queuing at the escape exits modelled.

If heavy vehicles were to be restricted to non congested hours the risk level would decrease to about 50% of the original risk. This risk level would be considered to be tolerable.

If heavy vehicles were to be banned from the tunnels the risk level would decrease to about 13% of the original risk level. This risk level would be considered to be acceptable.

7.5 Evacuation Capacity

Increasing the 1500 mm stair width modelled would reduce the fatalities in the scenarios investigated.

If the stair widths were to be increased to 2500mm the risk level would be decreased to about 76% of the original level. This measure is considered to have a beneficial effect on the risk level but the risk level would still be of concern.

7.6 Suppression

A water spray/mist suppression systems are not considered significantly increase passenger safety but do mitigate commercial loss.

8 General recommendations

8.1 Exclusion of Heavy Vehicles during Congestion

The feasibility of excluding heavy vehicles during morning and evening congested periods should be investigated.

The practicality of restricting, or eliminating, heavy vehicles should be carefully considered.

8.2 Evacuation Procedures

Evacuation procedures should be developed and rehearsed.

8.3 Evacuation, Audio and Signage

The use of broadcasts and other audible and visual systems to lead passengers to the exits in poor visibility should be investigated.

8.4 Smoke Extract Strategy

Smoke extract strategies should be developed to allow for traffic congestion. The ventilation/extract system should start automatically upon detection.

Two different ventilation strategies should be developed depending on if the traffic is congested or not. This measure is considered to have a significant impact on the risk level.

For congested traffic the longitudinal air velocities should be kept to a minimum and smoke should be extracted transversally. For non congested traffic the longitudinal air velocity should be high, > 3 m/s, and the smoke produced should be extracted further down in the tunnel (the next ventilation section).

8.5 Fire Detection and Smoke Extract Availability

The detection system and the smoke systems should be designed to a predetermined high availability on demand and a compatible test regime incorporated into the operating plan.

8.6 Safety Management System and Safety Case

A tunnel safety management system should be developed; part of this development is the creation of an Incident Management Plan.

8.7 Emergency Services

It is recommended that the tunnel design and evacuation plans are jointly developed as soon as possible with the emergency services.

The fire vehicle access should also be analyzed in more detail. It is considered that the vehicle access into the tunnel in case of an emergency will be very limited. Access to the tunnel will have to be via the emergency routes (this will have implications on water access etc).

8.8 Water spray/mist Suppression

It is recommended that water mist/sprays systems are investigated in detail and their cost effectiveness ascertained.

9 Safety equipment recommendations

The recommendations are based on the comparison and experience from similar projects. It is considered important that the tunnel operator, fire service and other relevant groups establish a task group to determine the necessary safety equipment provisions for the tunnel.

The different safety/protection systems for the tunnel are not yet finalised but the following systems are recommended.

Information regarding the safety equipment systems has been received during the preparation of this thesis, the additional comments are shown in **bold text**.

The safety equipment installations that are planned for the tunnel are in most cases over and above the recommendations provided.

9.1 Fire Detection Systems

The detection system is vital when it comes to tunnel safety. Many of the other systems used in the tunnel depend on the detection system for their operation (smoke extract system, evacuation systems, traffic management systems, etc.).

Different systems have been investigated: Linear heat detection, CO/CO2/NOX detectors. CCTV/IR (flame detection), Opacity detectors and smoke detectors.

It is recommended that a “line-type heat-detection cable with semiconductor temperature sensors (multi-point system)” should be used. We recommend that two independent line detectors will be installed above the inner and outer lanes to assist reliability and speed of detection. These systems activate an alarm upon a pre-programmed rate-of-rise and a maximum temperature principle. With this type of system it is normally possible to pin point the location of the fire to a few tens of metres.

High reliability can be anticipated for the recommended detection system, the coating of the cable protects against aggressive ambient and mechanical influence. The EN 54 standard [4] should be used when designing the system.

This type of system should be able to fulfil the following requirements:

- Detection cable length of 2000m.
- 30-60 s detection times.
- Guaranteed operation in case of cable breakage by fail safe functions.
- Monitored integration into a fire alarm system.
- Serial interface for temperature and data interchange to SCADA (Supervisory Control and Data Acquisition) systems.
- A maximum repair time of 30 min (change of affected segment) for mechanically damaged cable (performed by a technician once the lane is closed to traffic).

A heat detection cable is planned for the tunnel. This system seems to meet the requirements recommended.

9.2 Fire Fighting Systems

9.2.1 Extinguishers

Portable fire extinguishers are considered essential for first aid fire fighting as rapid intervention is very important. The spacing between extinguishers should not exceed 75m.

The portable extinguishers should be alarmed. If an extinguisher is removed from its support, an alarm signal will be sent to the control room. This alarm serves two purposes, as an extra measure to detect fires and signalling the potential theft of an extinguisher.

The tunnel will be equipped with portable extinguishers. The spacing between extinguishers is much less than the minimum distance recommended.

9.2.2 Hose reels

It is recommended that hose reels should be installed and placed together with the extinguishers (with a spacing not exceeding 75m). As with the extinguishers, the hose reels should be alarmed, i.e. the usage of a hose reel should send an alarm to the control room.

The tunnel will be equipped with portable hose reels.

Every hose reel is also equipped with an outlet to be used by the fire brigade if required; every emergency exit has 3 hoses (each 25m) for fire brigade use. The spacing between hose reels is much less than the minimum distance recommended.

9.2.3 Fire hydrants

A hydrant system should be incorporated into the tunnel (at a spacing not exceeding 150m). In addition to the hydrants within the tunnel there should be outlets in the escape stairs; these will serve the fire brigade when the fire cannot be approached via the tunnel.

Hydrants will not be used for first aid fire fighting; they are only for fire service use.

Fire hydrants will be placed at every emergency exit, in addition a dry riser will also be provided at each emergency exit. This is in line with the recommendations.

9.3 Suppression system

It is recommended that a suppression system should be investigated in detail for property protection (tunnel structure and tunnel systems), business continuity (tunnel closed due to repair work) and fire fighting.

If a suppression system is to be installed, it should be manually activated and only activated once the evacuation from the area is finished. Automatic activation is discouraged but it should be possible to effect a default time in case the operator is incapacitated. The system should have the capacity to function for at least 60 minutes.

The time of activation of the suppression system is important, it the system is activated early it will affect the evacuation (it is considered that the visibility will be heavily affected if the system is activated early and with the ventilation strategy adopted for the tunnel the late activation of the system is considered beneficial). If activated to late damage to the structure and the systems might have occurred. The time to reach high temperatures (temperatures high enough to damage to tunnel systems and the structure) is dependant of the severity of the fire but it should take at least 10 minutes before this happens (implied that local damage will occur).

It is considered that a suppression system would be very advantageous in the case of a heavy vehicle fire, for fires smaller than this the benefits of the system would be lower (this is due to the fact that smaller fires are not considered to have a big impact on the tunnel structure or the tunnel systems). A suppression system will most likely have a big impact on the down time of the tunnel in case of a heavy vehicle fire, the repair time is expected to be much shorter if a suppression system is installed.

A suppression system is being considered for some parts of the tunnel.

9.4 Electrical Power supply

A reliable power supply with multiple redundancies and back-up systems is recommended. The customary installation includes two independent high voltage supplies feeding two independent transformer sets. The low voltage supplies then feed half the load each but are capable of feeding the total load via an automatic transfer switch which activates on the loss of one supply. Back up diesel generators could be included to increase the reliability of the power supply.

Uninterruptible power supplies should be provided to power essential control equipment.

The main feeders should be located where they will not be liable to mechanical impact of fire. When infrastructure protection cannot be provided the use of fire rated cables should be considered.

The power supply arrangements for the tunnel seem to meet the requirements recommended.

9.5 Communication Systems

9.5.1 Emergency telephones

The emergency phones basically serve for reporting accidents in tunnels and as back up system, redundancy is necessary in order to achieve a high probability of the appropriate action to an emergency.

It is recommended that the tunnel is equipped with the emergency phones, due to the other systems that are recommended for the tunnel is considered sufficient with a distance of 300m between them.

The tunnel is equipped with emergency telephones. The system meets the requirements recommended.

9.5.2 Manual accident/fire alarm

It is recommended that the tunnel is equipped with manual push buttons and they should be placed at all emergency exits and together with the extinguishers/hose reels i.e. a maximum distance of 75m between them.

At this stage no detailed information has been given about the manual accident/fire alarm.

9.5.3 CCTV

It is recommended that CCTV is installed in the tunnel. The installation should cover the whole tunnel length. The CCTV permits rapid detection and verification of accidents, especially fires, this gives the tunnel operator an advantage when it comes to take the necessary decisions (actions to mitigate the consequences). The spacing between cameras should not exceed 150m (this also depends on the performance of the CCTV system).

The tunnel is equipped with CCTV. The system meets the requirements recommended.

9.5.4 Emergency signage

It is recommended that all exits are equipped with illuminated exits signs. The tunnel should be equipped with at least two directional signs between two exits, the directional signs should show the distance to each exit and it should be illuminated. To make it easier for people to find and choose an exit the exit signs should be equipped with green strobe/flashing lights. This will most likely reduce the evacuation time which is very important.

The traffic signage (electrical information panels) should be used to inform tunnel users of emergency situations. This could be especially helpful in situations when evacuation from the tunnel is necessary.

The tunnel will be equipped with emergency signage. The system meets the requirements recommended.

9.5.5 Voice Alarm System

It is recommended that a VA system (Voice Alarm system) is incorporated. Especially for tunnels it is important that the evacuation is started as early as possible, persons that are informed (via the VA system) at an early stage will reduce the decision making time and start their evacuation earlier.

It is important that the VA system it is combined with proper tunnel management procedures.

The tunnel will be equipped with a voice alarm system. The system meets the requirements recommended.

9.5.6 Radio communication

It is recommended that emergency services radio rebroadcast facilities are provided for the tunnel. Commercial radio rebroadcast facilities should be considered, this could be used to inform/alert the tunnel users during tunnel emergencies (safety messages, RDS radio broadcasting etc).

The tunnel will be equipped radio communication, both emergency and commercial systems. The system meets the requirements recommended.

9.6 Other measures

9.6.1 Speed limit

The tunnels will have a speed limit of 80 km/h and this is recognized as a positive measure. Monitoring of compliance with this and distances between vehicles should be implemented.

10 Difficulties with Quantitative Risk Analysis

The main difficulty with the QRA is the quality of the data. Most variables used in the analysis are associated with uncertainty. For this analysis it can roughly be said that there were three different areas associated with uncertainties:

1. Development of accident frequencies. Uncertainties associated with incident statistics.
2. Probability figures for technical systems. Uncertainties associated with failure probabilities for detection systems, ventilation systems, etc.
3. Development of consequence figures. Uncertainties associated with the prediction of fatalities.

It is important to take these uncertainties into account and deal with them. There are different ways to do this; some very basic and some very complex. A basic method could for example be to do a sensitivity analysis to see which parameters that have an important impact on the result. These parameters could later be given conservative figures. One additional measure would be to perform a Monte-Carlo analysis. The chosen method depends on the level of complexity of the QRA but also on the level of uncertainty that can be accepted.

For this analysis, the uncertainties were treated in a quite simple but effective way; parameters and assumptions were given values that were considered to be conservative. This can be an effective way to deal with uncertainties; the “drawback” is that the results will be on the conservative side as well. This might create problems if conservative risk criteria are used.

It is very important to recognise that a risk analysis will contain uncertainties. Depending on the complexity of the analysis, a high or low degree of uncertainty analysis is necessary. Pate-Cornell [12] has developed a “model” with six different levels of treatment of uncertainties; it gives a very good view of what kind of uncertainty analysis that could be used for different levels of complexity.

It is recommended that a detailed uncertainty analysis always is performed for a complex QRA.

11 Areas of future development

Based on this risk analysis it can be seen that there is a need for further development in some areas. Specifically the four following areas are of interest:

1. Incident statistics. There is a need to have better statistical information. It should be possible to harmonize the way in which data is collected and create publicly accessible data bases.
2. Consequence analysis. It is very difficult to reliably predict number of fatalities and injuries due to fires. It is difficult to establish the effects of hazardous conditions on humans. This leads to different ways of predicting fatalities and for the same scenario it could be a large difference in the number of fatalities depending on the method that is used. There is a need to develop one or several standard models or methods (it could be based on visibility, temperature, etc.).
3. Fire scenarios. A fire could develop in many different ways. Common design fires based on the different types of vehicles should be developed. The heat release rate has a great impact on hazardous conditions.
4. Risk criteria. At the moment different countries have different risk criteria and some have none. A level of harmonization would be beneficial.

There is a real need for development in these areas. It is necessary, to some degree, with standardised methods, models, criteria, etc. to be able perform reliable and acceptable QRA´S.

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Appendix A

Broad Evaluation Calculations

A1 Evaluation of risk, sections

The following table shows the results from the semi quantitative analysis that was carried out to see if there was any significant difference in risk level between the different segments.

The different segments were examined having the different factors in mind. Each segment was scored on the factor. A grading from 1 to 4 was used, 1 being the safest and 4 being the most risky.

	Segment						
Factor	2/3 Interior	2/3 Exterior	4 Interior	4 Exterior	5 Interior	5 Exterior	1 Exterior Interior
On/ Off ramps	4	4	2	2	4	1	1
Slope	4	3	2	3	1	1	3
Length	4	4	2	3	2	2	4
Curvature	3	3	3	3	2	2	1
Risk Number	3.910	3.610	2.090	2.500	2.700	1.200	1.930
Normalized Risk Number (NRN)	3.26	3.01	1.74	2.08	2.25	1.00	1.61

Table A1 Risk Number

Appendix B

Semi Quantified Methodology

B1 Semi Quantified Risk Register

The risk register was compiled using the following tables.

Frequency categories	
Class	**Description**
F1 - Improbable	1 incident per 10 000 years
F2 - Rare	1 incident per 1000 years
F3 - Unlikely	1 incident per 100 years
F4 - Likely	1 incident per 10 years
F5 - Frequent	1 to 10 incidents per year

Table B1 Frequency

Consequence categories	
Classification	**Description**
C1 - Minor	First aid treatment required
C2 - Major	Medical treatment required
C3 - Severe	1 or more severe injuries
C4 - Serious	1 or more fatalities, or numerous severe injuries
C5 - Critical	More than 10 fatalities

Table B2 Consequence

	Consequence (C)				
Frequency (F)	1	2	3	4	5
1	C	C	C	C	B
2	C	C	C	B	B
3	C	C	B	B	A
4	C	B	B	A	A
5	B	B	A	A	A

Table B3 Risk Matrix

Appendix C

Risk Register

C1 Risk Register

The following figures show the risk register (Hazard Log).

Hazard Log

Haz No	Section / part of tunnel	Hazard	Hazard event/scenario	Consequence	Initial Mitigation	Existing Risk F	Existing Risk C	Existing Risk R	Proposed Additional Mitigation	New Risk F	New Risk C	New Risk R	Remarks	Modelling Run
1	All sections	Light and heavy vehicles	collision (no congestion)	1 or more fatalities	Traffic management, Signage, Speed control, CCTV,	4	4	A	Enforcment of speed limit of 80 kph	3	4	B	Approximately 3 fatalities per year on Calle 30, therefore 0.6 for the 6 km under consideration	N/A
2	All sections	Light and heavy vehicles	collision (congestion)	Medical treatment required	Traffic management, Signage, Speed control, CCTV,	3	3	B	No further mitigation proposed	3	3	B	Congestion 10% of time, lower speed collisions	N/A
3	All sections	Light vehicles	single LV fire (no congestion)	First aid treatment required	Detection system, Ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	5	1	B	No further mitigation proposed	5	1	B	A few small fires expected per year	Evaluated with runs described for Haz No 6
4	All sections	Light vehicles	single LV fire (congestion)	Medical treatment required	Detection system, Ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	4	2	B	No further mitigation proposed	4	2	B	Congestion 10% of time but greater injury due to number of people who have to evacuate	Evaluated with runs described for Haz No 6
5	All sections	Light vehicles	multiple LV fire (no congestion)	1 or more severe injuries	Detection system, Ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	4	3	B	No further mitigation proposed	4	3	B	Frequency 10% of #3 but greater consequence	Evaluated with runs described for Haz No 6
6	All sections	Light vehicles	multiple LV fire (congestion)	1 or more fatalities	Detection system, Ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	3	4	B	3 no. 30 m drencher sections activated	3	3	B	Frequency 10% of #4 but greater consequence	7 MW + Ventilation (early and late activation), FDS runs 1 and 7
7	All sections	Light vehicles	single LV fire (no congestion)	First aid treatment required	Detection system, Degraded ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	3	1	C	No further mitigation proposed	3	1	C	Frequency 1% of #3, degraded ventilation adequate for single LV fire	Evaluated with runs described for Haz No 10
8	All sections	Light vehicles	single LV fire (congestion)	Medical treatment required	Detection system, Degraded ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	2	2	C	No further mitigation proposed	2	2	C	Frequency 1% of #4, degraded ventilation adequate for single LV fire	Evaluated with runs described for Haz No 10
9	All sections	Light vehicles	multiple LV fire (no congestion)	1 or more fatalities	Detection system, Degraded ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	2	4	B	3 no. 30 m drencher sections activated	2	3	C	Frequency 1% of #5, degraded ventilation inadequate for multiple LV fire	Evaluated with runs described for Haz No 10
10	All sections	Light vehicles	multiple LV fire (congestion)	1 or more fatalities	Detection system, Degraded ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	1	4	C	3 no. 30 m drencher sections activated	1	3	C	Frequency 1% of #6, degraded ventilation adequate for multiple LV fire	7 MW + degraded ventilation (early activation), FDS run 3

11	All sections	Heavy vehicles	single HV fire (no congestion)	Medical treatment required	Detection system, Ventilation system, Suppression system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	4	2	B	No further mitigation proposed	4	2	B	HVs are taken to be 10% of LVs, injury greater than #3 (same accident but for LVs)	Evaluated with runs described for Haz No 12 and 14
12	All sections	Heavy vehicles	single HV fire (congestion)	1 or more severe injuries	Detection system, Ventilation system, Suppression system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	3	3	B	No further mitigation proposed	3	3	B	Congestion 10% of time, lower speed collisions	30 MW + ventilation (early activation) + suppression system / no suppression system (water spray, water mist), FDS runs 2, 5 and 6
13	All sections	Heavy vehicles	multiple HV fire (no congestion)	1 or more fatalities	Detection system, Ventilation system, Suppression system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	3	4	B	3 no. 30 m drencher sections activated	3	3	B	HVs 10% of LVs	Evaluated with runs described for Haz No 12 and 14
14	All sections	Heavy vehicles	multiple HV fire (congestion)	More than 10 fatalities	Detection system, Ventilation system, Suppression system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	2	5	B	3 no. 30 m drencher sections activated	2	4	B	HVs 10% of LVs, multiple deaths	70 MW + degraded ventilation (early activation, failure due to heat), FDS run 8
15	All sections	Heavy vehicles	single HV fire (no congestion)	1 or more severe injuries	Detection system, Degraded ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	2	3	C	No further mitigation proposed	2	3	C	Frequency 1% of #11, degraded ventilation in adequate for single HV fire	Evaluated with runs described for Haz No 14 and 16
16	All sections	Heavy vehicles	single HV fire (congestion)	More than 10 fatalities	Detection system, Degraded ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	1	5	B	3 no. 30 m drencher sections activated	1	4	C	Frequency 1% of #12, degraded ventilation inadequate for single HV fire	30 MW + degraded ventilation (early activation), FDS run 4
17	All sections	Heavy vehicles	multiple HV fire (no congestion)	1 or more fatalities	Detection system, Degraded ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	1	4	C	3 no. 30 m drencher sections activated	1	3	C	Frequency 1% of #13, degraded ventilation adequate for multiple HV fire	Evaluated with runs described for Haz No 14 and 16
18	All sections	Heavy vehicles	multiple HV fire (congestion)	More than 10 fatalities	Detection system, Degraded ventilation system, Emergency exits, Signage, CCTV, hydrants, hose reels, extinguishers	1	5	B	3 no. 30 m drencher sections activated	1	4	C	Frequency 1% of #14, degraded ventilation inadequate for multiple HV fire	Evaluated with runs described for Haz No 14 and 16

Appendix D

Frequencies and Probabilities

D1 Input data

D1.1 Frequencies

The different frequencies used in the analysis are based on data from a number of different tunnels worldwide and a French tunnel study. Information is taken from a PIARC document [1].

Based on information in the PIARC document data for unidirectional tunnels longer than 1000m was listed, the following table shows the result. The first 13 tunnels are urban and the 3 last ones are rural.

Land	Tunnel	Length (m)	Years	Average Annual Traffic (million veh / year)	Total traffic work per year (million veh km / year)	Rate per 100 million vehicle km		
						PV	Lorries	All
Canada	Ville-Marie	2800	1991-1988	28.50	79.80	-	-	0.3
	L. Hippolyte	1400	1987-1991	40.00	56.00	0	0	0
France	Croix Rousse	1800	1985-1991	29.40	52.92	2	0	1.8
	Fourviere	1800	1985-1991	34.90	62.82	1.8	1.9	1.8
Germany	Elbe	3300	1990-1991	37.00	122.10	6.3	24.6	9
Nether lands	Benelux	1300	1986-1988	25.00	32.50	0	0	0
	Coen	1200	1986-1988	30.00	36.00	0	0	0
Norway	Oslo	1800	1990-1993	18.30	32.94	-	-	2
Sweden	Soder	1100	1987-1991	25.60	28.16	-	-	0.7
UK	Tyne	1700	1987-1992	9.70	16.49	-	-	25
USA	Brooklyn Battery	3200	1989-1991	21.00	67.20	-	-	23
	Queens Midtown	2800	1989-1991	26.40	73.92	-	-	14
	Lincoln	2500	1987-1991	38.30	95.75	-	-	15
Average						**1.68**	**4.42**	**7.12**
France	Dullin	1500	1984-1991	7.3	10.95	1.6	0	1.3
	Vuache	1400	1990-1993	4.8	6.72	3	0	2
	St. Germain	1200	1990-1992	6	7.20	0	3.4	8.1
Average						**1.53**	**1.13**	**3.8**

Table D1 Frequencies

A French study including 26 tunnels are also documented in the PIARC document. The following table shows the result from that study.

Classification of fire		**Cases of fire for 100 million vehicle km**
Passenger cars	Fires of any importance	1.5
Lorries	Fires of any importance	8
	Fires with some damage to the tunnel	1
	Very serious fires	0.2
Lorries with dangerous goods	Fires	2
	Fires involving dangerous goods	0.3

Table D2 Frequencies

Based on the two tables above it was determined to use the following frequencies.

- **Light vehicles: 1.5 small fires per 100 million vehicle km**
- **Heavy vehicles: 9.2 small fires per 100 million vehicle km**

The average daily traffic for the relevant part of the motorway is calculated from historical data [2]. The tunnel is considered to be located approximately between P.K 18 and P.K 13 of the motorway. The following table shows the calculated average daily traffic used (both directions).

Year	**Section of Highway**	**Average Daily Traffic**
1999	P.K 18 to P.K 13	194 910
2003	P.K 18 to P.K 13	191 402
Value used for calculation (average of years 1999 and 2003)		*193 156*

Table D3 Traffic data

Traffic prediction figures for 2007 were given but these were not that detailed so the traffic figures used in the calculations were estimated based on historical data.

The initial frequency used for the event trees is based on the predicted traffic flow for the tunnel (both directions); the following table shows the predicted flow.

Vehicle type	Traffic flow (vehicles per day)	Tunnel length (km)	Predicted flow (million vehicles km per year)
Heavy vehicle	13 520 (7%)	Approx. 6	29.6
Light vehicle	179 636 (93%)	Approx 6	393.4
Total	*193 156*		423

Table D4 Predicted flow 2007

The following table shows the initial frequencies used.

Vehicle type	Traffic mode	Frequency (fires per 100 million vehicle km)	Predicted flow (million vehicles km per year)	Frequency (small fires per year)
Heavy vehicle	Congested	9.2	7.4	0.68
Heavy vehicle	Not congested	9.2	22.2	2.04
Light vehicle	Congested	1.5	98.2	1.47
Light vehicle	Not congested	1.5	294.7	4.42

Table D5 Frequencies of small fires

D1.2 Probabilities

Probability figures used in the analysis is mainly based on historical data, when no historical data have been available engineering judgement has been used. Most of the system probabilities are based on historical data taken from PD 7974-7:2003 [3].

D1.2.1 Fault trees

The following probabilities have been used for the fault trees.

- Detection system (not working): 0.1 (from PD 7974, fire alarm and detection systems). Figure is considered to be conservative as it is assumed that the system does self checks every 10 seconds and have a power backup.
- Call points (not working): 0.1 (from PD 7974, fire alarm and detection system). The value for call points has been assumed to be slightly lower than for alarm boxes and wiring.
- Alarm on FAFF equipment (not working): 0.1 (from PD 7974, fire alarm and detection system). The value for the alarm has been assumed to be slightly lower than for alarm boxes and wiring.
- Manuel system (not used): 0.3, It is considered that people will use the manual system (fire extinguishers, hose reels, alarm push buttons, etc). The value used is considered to be conservative as it assumes that people won’t use the systems in 3 out of 10 times.

- CCTV system (not working): 0.1, Value assumed to be conservative as faulty systems (cameras etc) will be repaired as soon as detected faulty.
- Looking at CCTV but fire is not detected: 0.5 and 0.9, For failure of detection (fire not detected) a conservative value of 0.5 is used. It is considered that trained personnel will perform better than this. For early detection (detection within 60 seconds) a conservative value of 0.9 has been used. In general human error rates are lower but for conservative reasons quite high values have been used.
- Not looking at CCTV: 0.3, It is assumed that personnel wont be able to check the CCTV at all times. A high value of 0.3 ha been used (not looking at monitors 30% of the time).
- Failure of system (fire fans): 0.1, (from PD 7974, smoke control systems). A general value for failure of operation of smoke control systems has been used. The figure is considered to be conservative as it is assumed that the system will be controlled and checked regularly.

D1.2.2 Event trees

The probabilities used for the event trees are based on figures from PIARC [1], PD 7974-7:2003 [3] and the results from the fault trees. The following probabilities have been used.

- Fire development (fire is extinguished):
    - Light vehicles: 0.4, French studies shows that 40 % of fires in tunnels are extinguished (interpreted as no fatalities) i.e. no need for fire brigade intervention. (PIARC document).
    - Heavy vehicles: 0.87, French studies regarding heavy vehicle fires show that about 87% cause no damage to the tunnel, 11% caused some damage to the tunnel and are estimated to be below 20 MW, the rest (2%) were very serious fires which are estimated to be above 20MW. This is interpreted as if 87% of the heavy vehicle fires were small and classified as extinguished i.e. no fatalities. (PIARC document)
- Detection (within 60 seconds): 0.99, It is assumed that all fires will be detected (based on results from the fault tree analysis). However, it is considered that it could be a difference in detection time. The fault tree analysis shows that early detection (within 60 seconds) will most likely occur in 99% of all cases.
- Fire ventilation (not going into full fire mode): 0.1, It is assumed that the ventilation system always will be able to go into partial mode (only failure of the fire fans), the fans used for the partial mode are used daily and if failure occurs it will be detected immediately and it is assumed that the fans will be replaced/repaired as soon as possible. The fault tree analysis shows that the ventilation system is expected to go into full fire mode 9 out of 10 times.

D1.3 Fault trees

The following figures show the different fault trees used in the analysis.

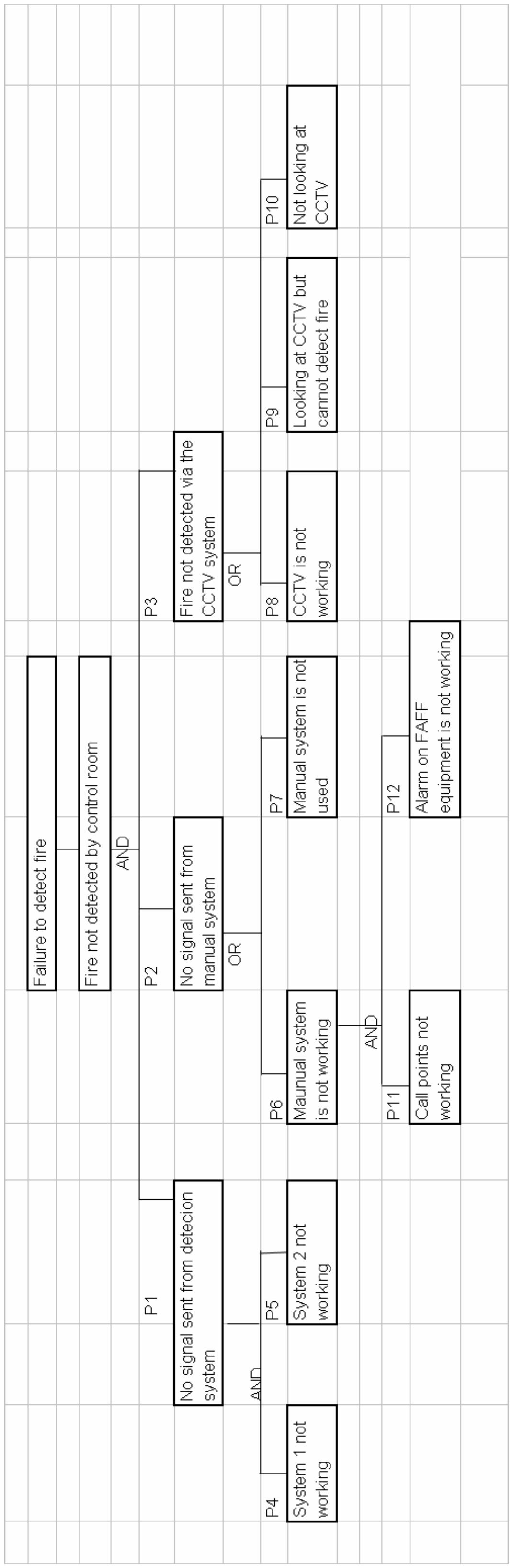
The following assumptions are made for the fault trees:

- Signals sent to the control room is detected.
- "System not working" include failure of wiring etc.
- Signals sent from the detection system will reach the ventilation fans.

The following sections show the three different fault trees.

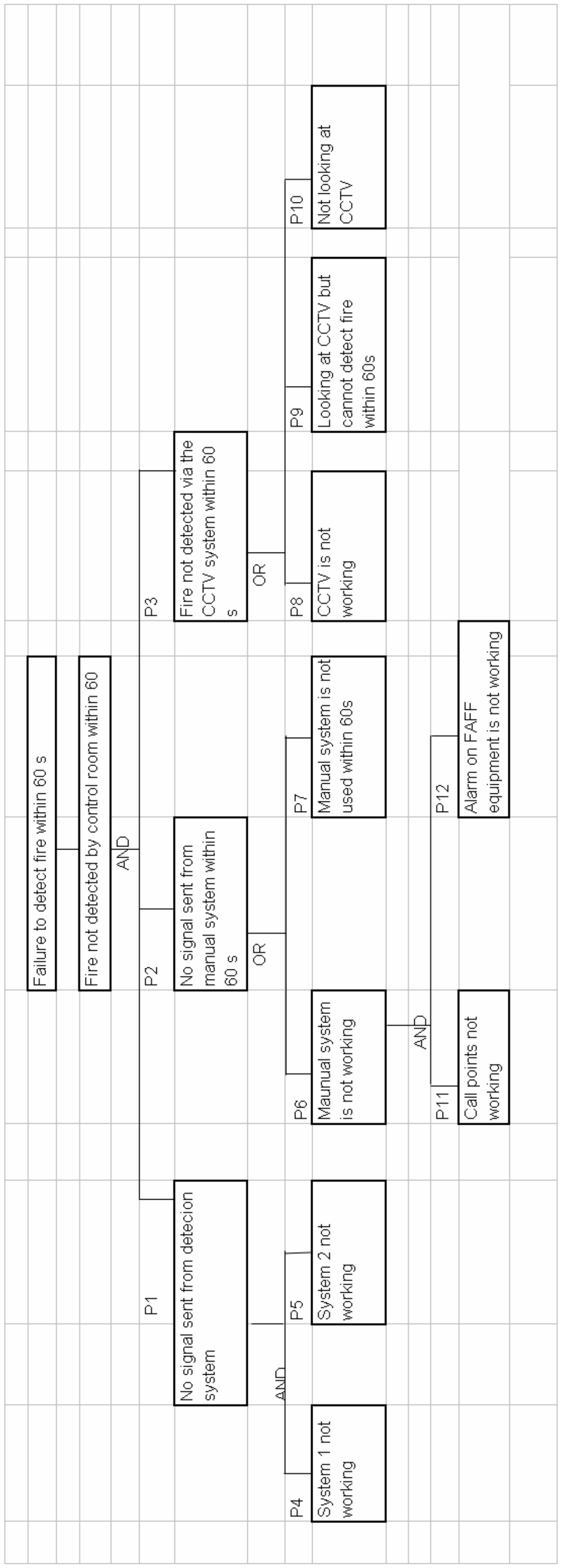
D1.3.1 Fault tree 1, Failure to detect fire

The probability of the top event (failure to detect fire) is 0.0027 (0.27%).



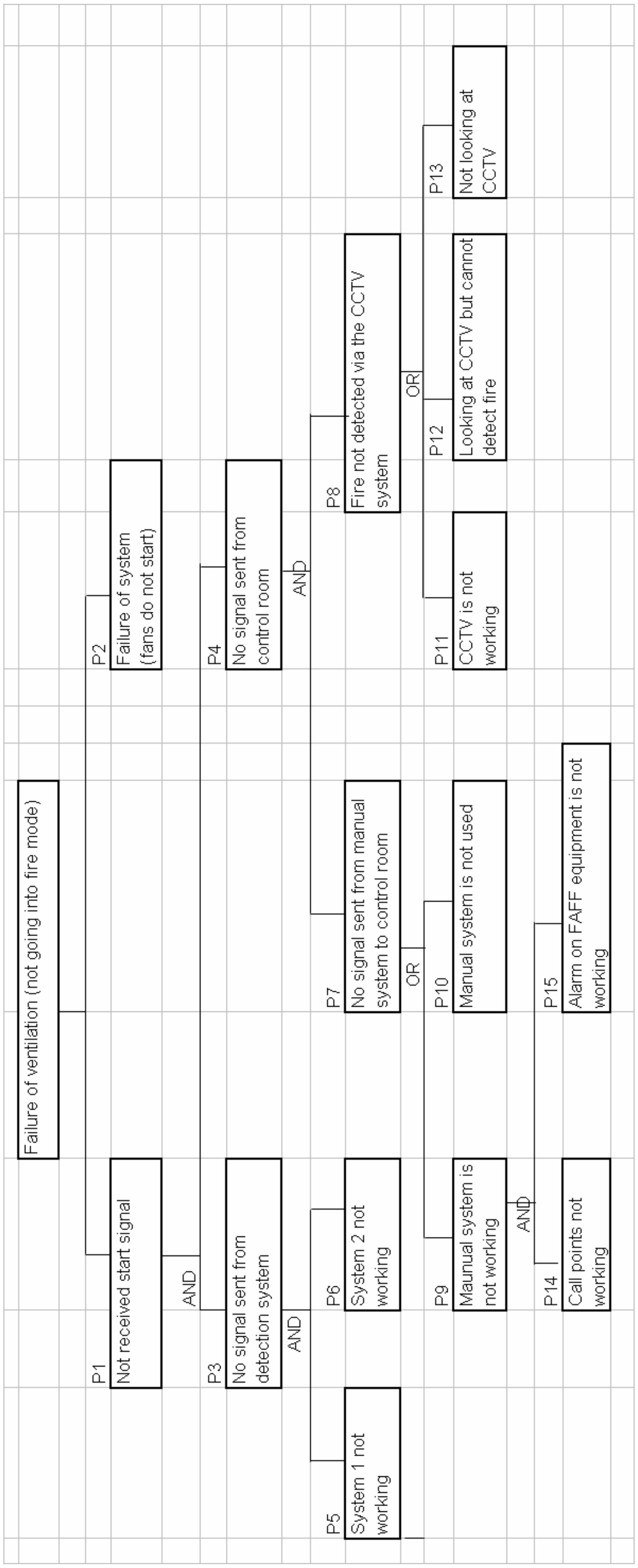
D1.3.2 Fault tree 2, Failure to detect fire within 60 s

The probability of the top event (failure to detect fire within 60 s) is 0.0115 (1.15%).



D1.3.3 Fault tree 3, Failure of ventilation (no start of fire fans)

The probability of the top event (failure of ventilation) is between 0.1024 and 0.1035. (10%).



D2 References

[1] PIARC, Fire and Smoke Control in Road Tunnels, 1999

[2] Anuario estadístico de accidentes en las carreteras del estado, 1991-2003, Ministerio de Fomento (Dirección General de Carreteras), Spain

[3] Application of fire safety engineering principles to the design of buildings – Part 7: Probabilistic risk assessment, PD 7974-7:2003

Appendix E

Event trees

E1 Event tree analysis

The following sections show the detailed event trees used for this analysis.

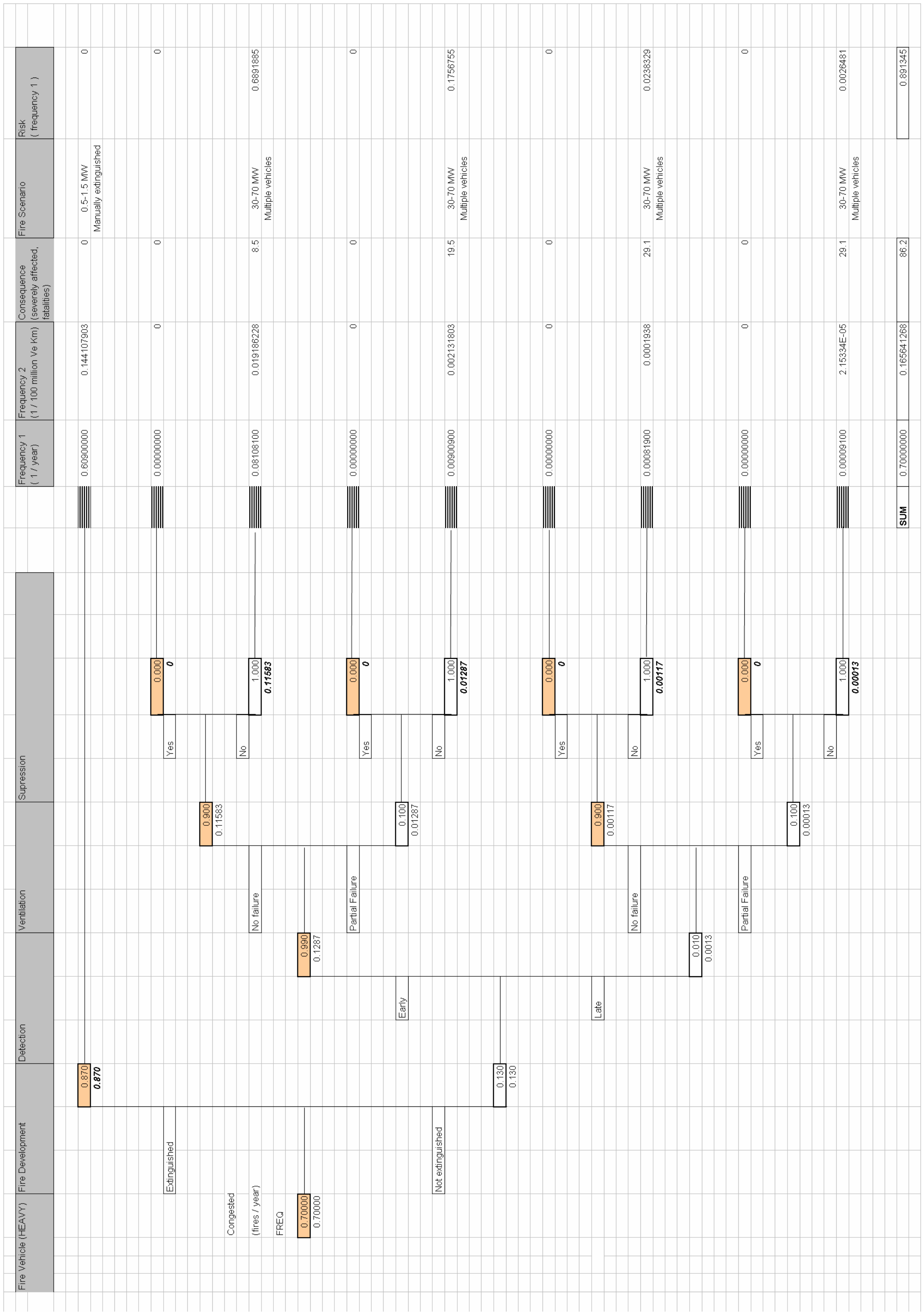
E1.1 Input

There are three main input parameters needed for the event trees.

- Frequencies: Frequencies for the initial event of the event tree need to be given. The frequencies used for these event trees are “fires per year”. See Appendix D.
- Probabilities: Failure and success probabilities are needed for the different branches of the event tree. See Appendix D
- Consequences: Consequence figures for the different end scenarios are needed. The consequence modelling is not shown in detail for this report; only the consequence numbers are used. The consequence numbers are used as input for the event trees.

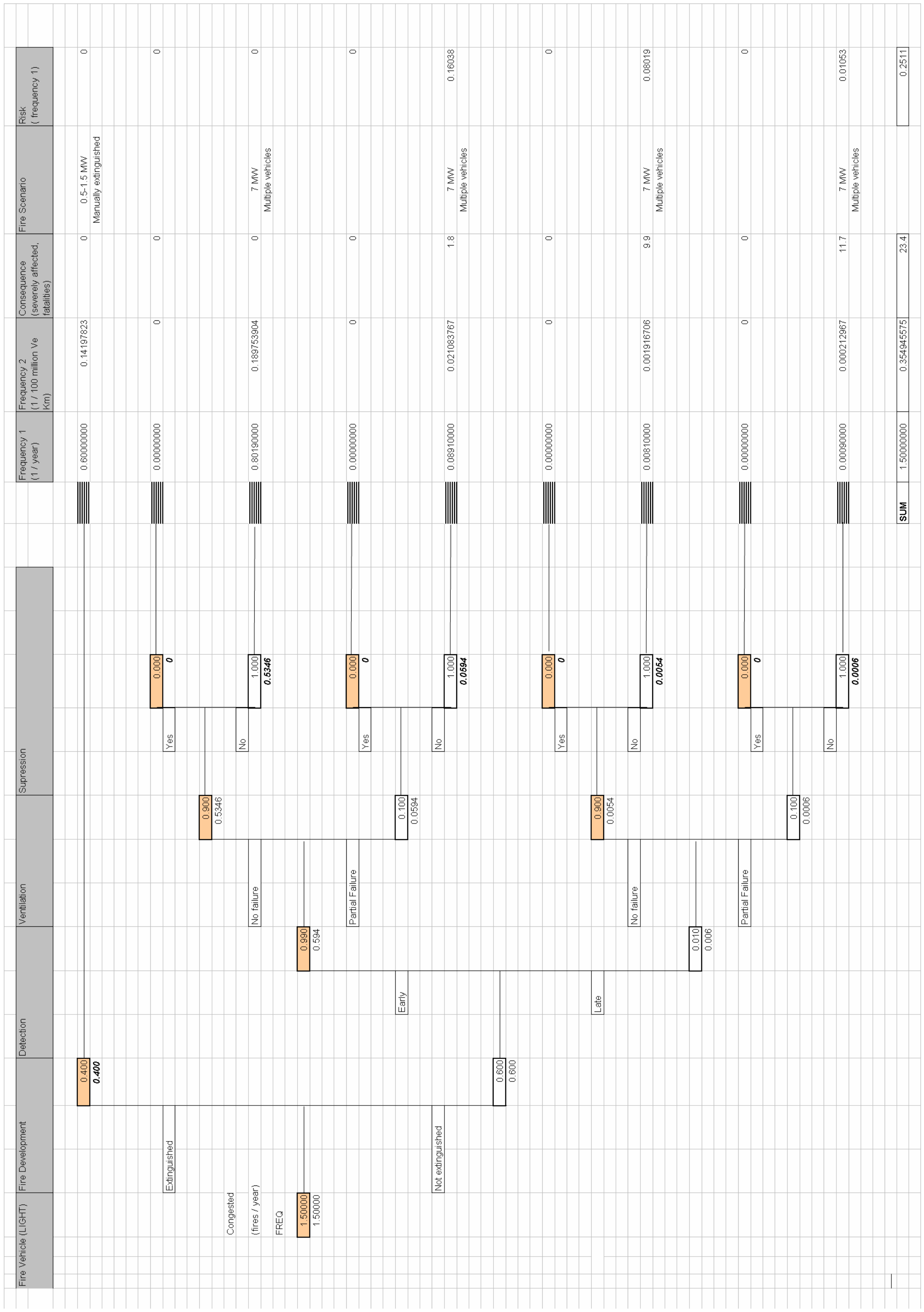
E1.2 Event trees

E1.2.1 Heavy vehicle, congested, no suppression



E1.2.2 Heavy vehicle, not congested, no suppression

E1.2.3 Light vehicle, congested, no suppression



E1.2.4 Light vehicle, not congested, no suppression

Appendix F

Risk Benchmarks

F1 Development of risk benchmarks

Risk criteria can be presented and expressed in many different ways depending on what units that are used. There are very few established risk criteria for traffic and there are no internationally agreed criteria.

As no risk criteria for an acceptable level of risk to life within road tunnels were given by the client special risk criteria have been developed, they are based on risk criteria (constructed for traffic) from Norway and Austria. Also historical data from the motorway in question has been used to determine the risk criteria.

The criteria used to evaluate the risks within the tunnel are shown below. Two criteria are used to evaluate the individual risk and two criteria are used to evaluate the societal risk. It must be pointed out the criteria constructed are based on all type of road accidents, not only fire accidents.

F1.1 Individual risk

The individual risk is presented as fatality per vehicle km.

F1.1.1 Existing level

Historical data [1] were used to establish the individual risk level for the motorway.

The historical data is shown below:

Year	Number of deaths	Vehicle Km (10^3)
2003	2	1760266
2002	8	1959075
2001	10	1941375
2000	8	1884595
1999	4	1819746
1998	9	1674296
1997	9	1722318
1996	4	1673497
1995	12	1639257
1994	21	1706374
Total	**87**	**17780799**

Table F1 Historical data

The historical rate for all accidents (fires and road accidents) is

- **0.5 fatalities/ 100 million vehicle kilometres**

F1.1.2 Norway

The individual risk criteria is developed with historical data and an acceptance criterion for individual risk used in Norway [2].

The historic level in Norwegian tunnels is 4 fatalities per 1000 million person km [2].

A person km is one km travelled by one person, a vehicle km is one km travelled by a vehicle. For this analysis it is assumed that there are 2.5 persons per vehicle i.e. 1 vehicle km correspond to 2.5 person km.

By making the assumption that one vehicle km is equivalent to 2.5 person km the Norwegian rate can be transformed into a fatality per vehicle km figure.

- **1.0 fatalities/ 100 million vehicle kilometres**

This rate is 2 times the historical rate calculated above (for the motorway). This rate is not surprising as the tunnels are acknowledged as being less safe than open road.

The statistics show that approximately 25 % of the fatalities are due to fire and 75% due to other road accidents

The Norwegian acceptance criterion for individual risk (all traffic accidents) equates to

- 0.5 fatalities / 100 million vehicle kilometres

There is no evidence that this criterion is being achieved.

F1.1.3 Benchmark

The table below compares the researched data, (all per 100 million vehicle kilometres)

Historical Motorway (all accidents)	Norwegian Tunnels historical (all accidents)	Norwegian Tunnels historical (fires only)
0.5	1.0	0.3

Table F2 Benchmark

It is not within the scope of this study to set criteria but the most useful figures is the value for Fire in Norwegian Tunnels of

- **0.3 fatalities/ 100 million vehicle kilometres**

F1.2 Societal risk

The societal risk criteria developed is based on criteria from Norway and Austria. These criteria are based on FN curves. FN curves normally show the relationship between the accident Frequency and Number of fatalities.

Normally two different threshold lines are shown on an FN diagram, an upper limit and a lower limit. The area above the upper limit is considered non tolerable (undesirable), the area below the lower limit is considered tolerable and the area between the two limits are the ALARP area (As Low As Reasonably Practical). Risks in the ALARP area only need to be reduced if the approach can be shown to be reasonably practical.

The slopes of the lines are quite important. If the slope is greater than -1 it means that risk aversion is built into the curve i.e. the criteria reflects that the public avoids catastrophes (small frequent accidents are more tolerable than big infrequent accidents).

F1.2.1 Norway

The following criterion is proposed by the Public Road administration in Oslo [2]. The frequency used is fatal accidents per 1000 million person km. The slope is - 4/3. The expected value from the Norwegian criterion is about 1.98 fatalities per 1000 million person km. The historic level in Norway is 6 fatalities per 1000 million person km [3]. From this it can be concluded that the Norwegian criteria is very conservative, and it is important to keep that in mind when using it.

For this analysis the upper and lower limits were slightly adjusted and then the frequency used was transformed to fatality per 100 million vehicle km.

The fist step that needs to be done is to convert the person km figure to vehicle km. For the analysis it is assumed that 1 vehicle km is 2.5 person km (2.5 persons per vehicle). This means that 1000 million person km is equal to 400 million vehicle km. The next step is to adjust the lines to show the frequency for 100 million vehicle km, this is done by adjusting the frequency by a factor of 0.25 (100/400=0.25).

The following graph shows the transformed F/N curve for Norway. This curve is used in comparison in the main report

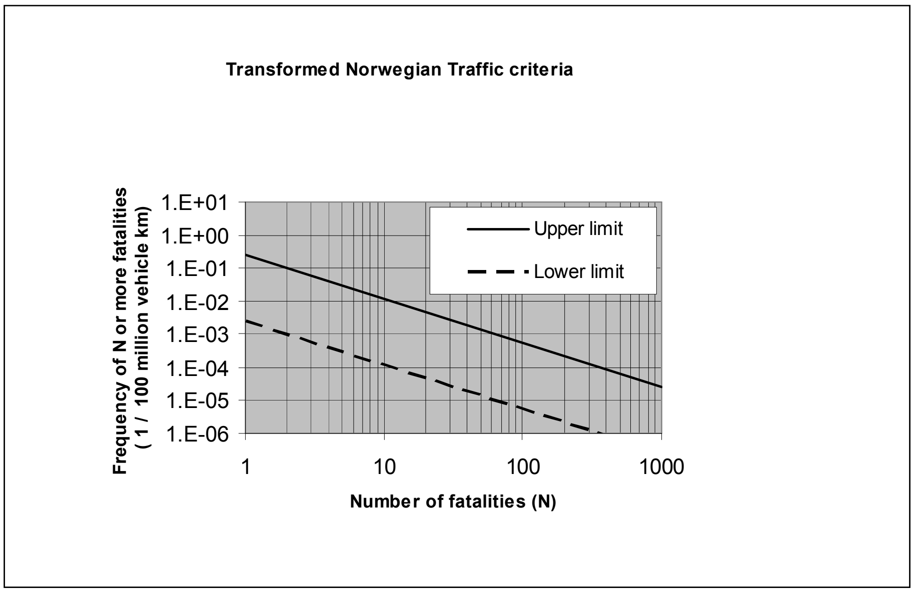


Figure F1 Transformed Norwegian criteria

F1.2.2 Austria

The Austrian Commission for Tunnel Safety [4] has suggested criteria for all accidents in a 1 km stretch of tunnel. The frequency used is fatal accidents per year. The slope is -1.

The following graph has been transformed to a tunnel length of 12 km (both directions, approx 6km + 6 km).

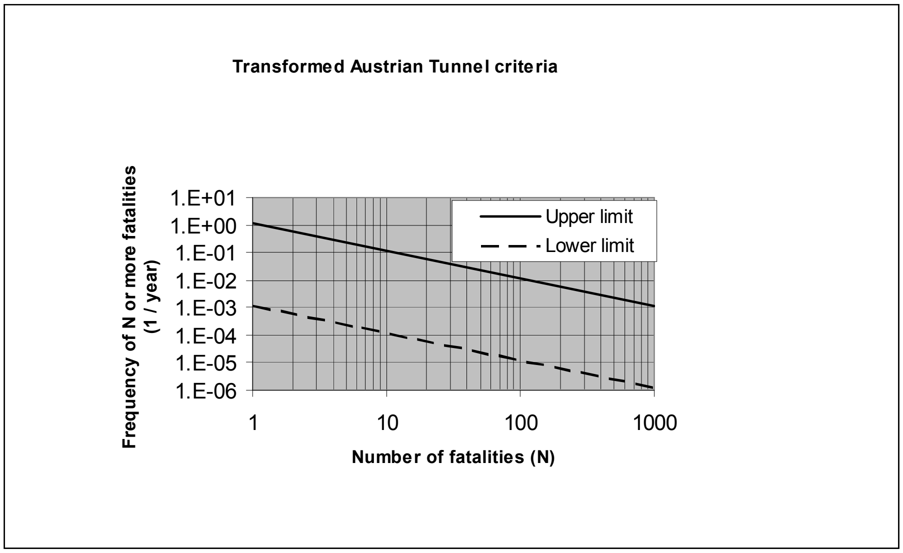


Figure F2 Transformed Austrian criteria

F1.2.3 Benchmark

The Norwegian and Austrian criteria noted above use different basis (Norway is per vehicle kilometre and Austria is per year). The Norwegian criteria are aspiratory and will not necessarily be met for this project.

They are not readily interchangeable and so both will be used for comparison in the main report

F2 References

[1] Anuario estadístico de accidentes en las carreteras del estado, 1994-2003, Ministerio de Fomento (Dirección General de Carreteras), Spain

[2] NVF Seminar "Infrastruktur I storstadsmiljo", 29/08/2002 (E18 – Bjorvikatunnelen – sikkerhetsforhold), Statens Vegvesen Oslo. Online (March/2006): http://www.vv.se/filer/publikationer/BAsikkerhetSkrivskyddad].pdf

[3] Bruk av risikoanalyser – document nr. 7 (Revisjon 3), Amundsen, F. et al, Vegdirektoratet – Jernbaneverket – Kystverket – Luftfartsverket – Sjofartsdirektoratet – Politidirektoratet, Norway, 2002

[4] "A comparative risk analysis for selected Austrian tunnels" , 2nd International Conference (Tunnel Safety and Ventilation), 2004, Graz. Online (March/2006): http://www.piarc.org/en/technical-committees/C3.3/qra_model/

Appendix G

F N Curves

G1 FN Curves

G1.1 Original curves (mitigation measures not included)

The two following figures shows the FN curves developed, no mitigation measures are included.

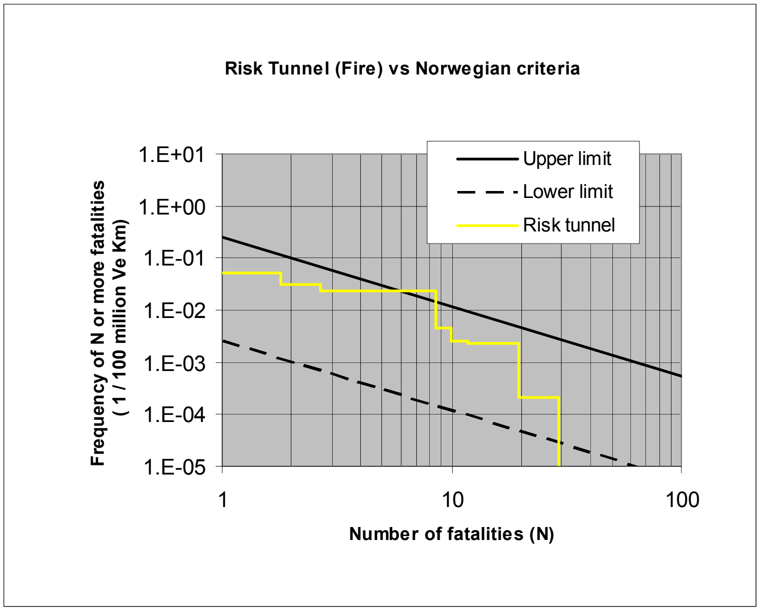


Figure G1 **FN curve**

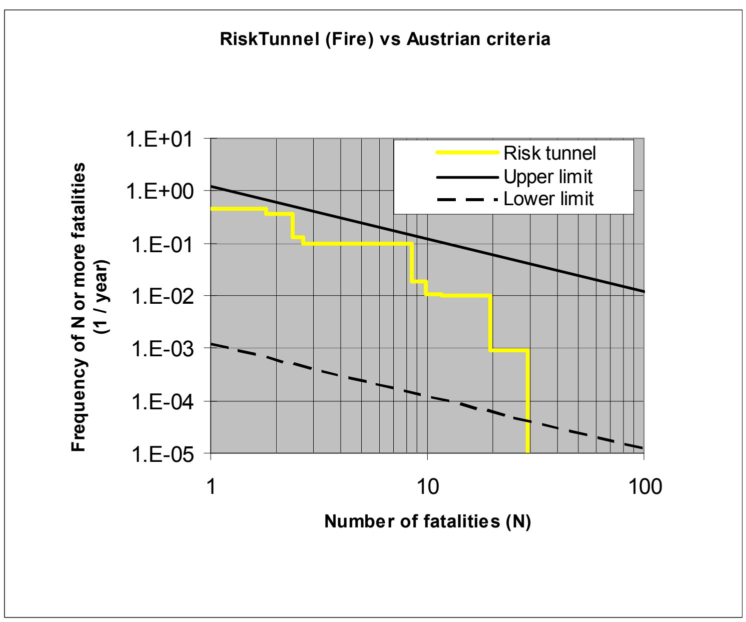


Figure G2 **FN curve**

G1.2 Original curves + Mitigation curves (mitigation measures included)

This section will show the different curves developed when the mitigation measures are included.

The following tables show the result of the mitigation measures.

	Expected Value (fatalities per year)	**Risk Level**
Original (No mitigation measurers)	1.77	100%
Heavy vehicles not permitted in the tunnel	0.25	14%
Heavy vehicles not permitted during congested hours	0.88	50%
Increased exit widths (2500mm)	1.35	76%
	Expected Value (fatalities per 100 million Ve Km)	**Risk Level**
Original (No mitigation measurers)	0.42	100%
Heavy vehicles not permitted in the tunnel	0.05	12%
Heavy vehicles not permitted during congested hours	0.20	48%
Increased exit widths (2500mm)	0.32	76%

Table G3 Risk level

G1.2.1 FN curves – No heavy vehicles in the tunnel

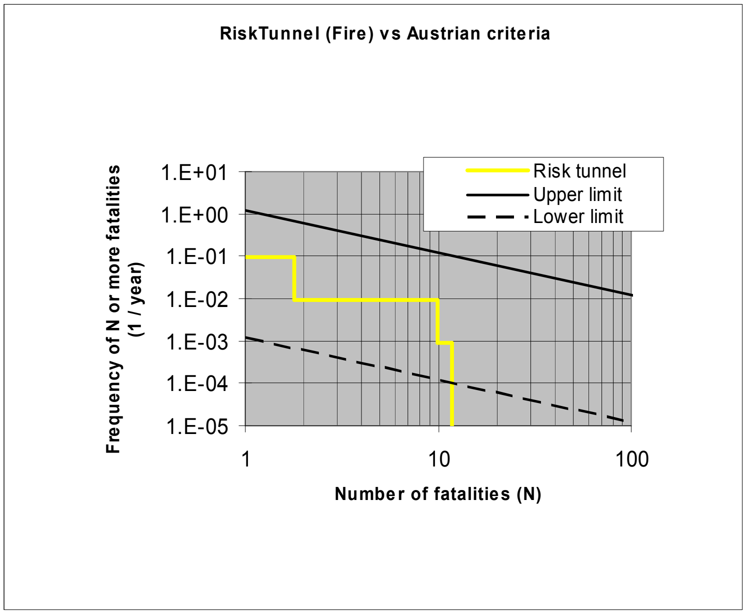


Figure G4

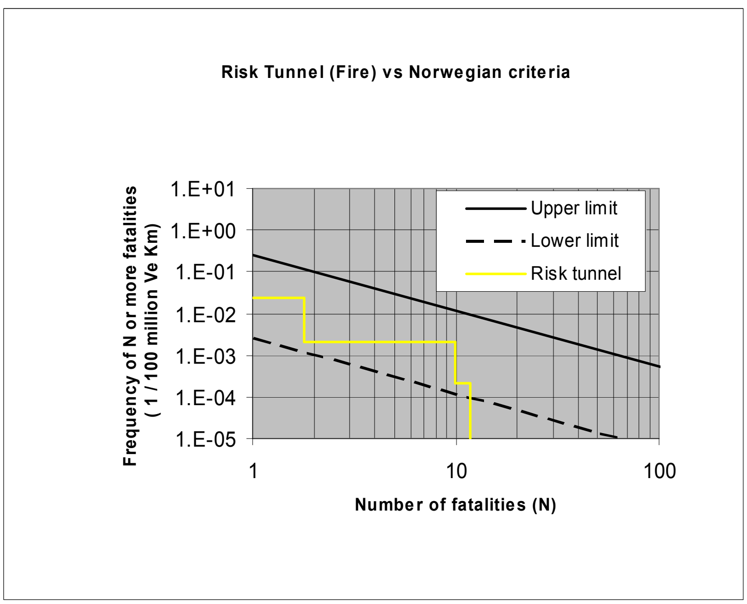


Figure G5

G1.2.2 FN curves – No heavy vehicles during congested hours

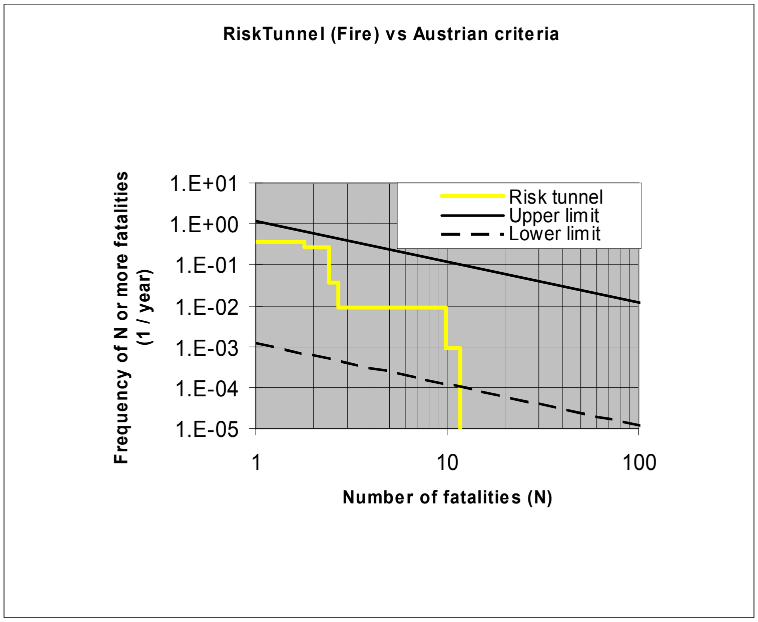


Figure G6

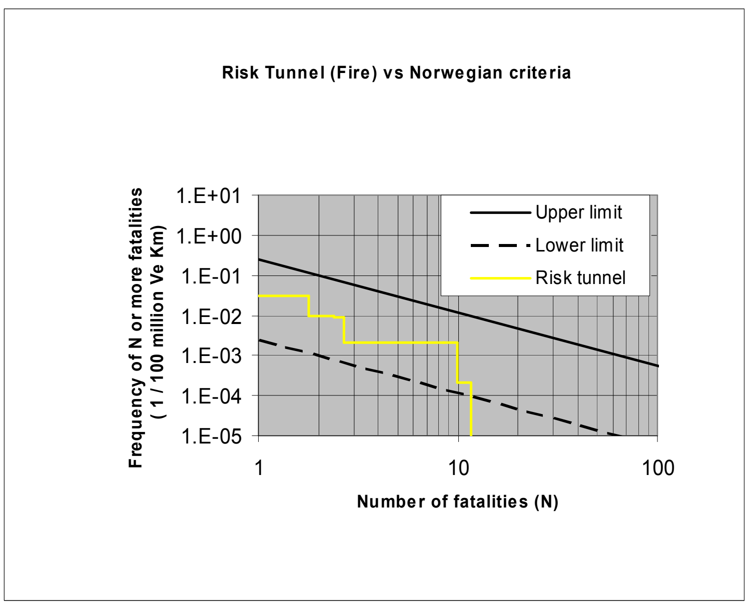


Figure G7

G1.2.3 FN curves – Increased exit widths (2500mm)

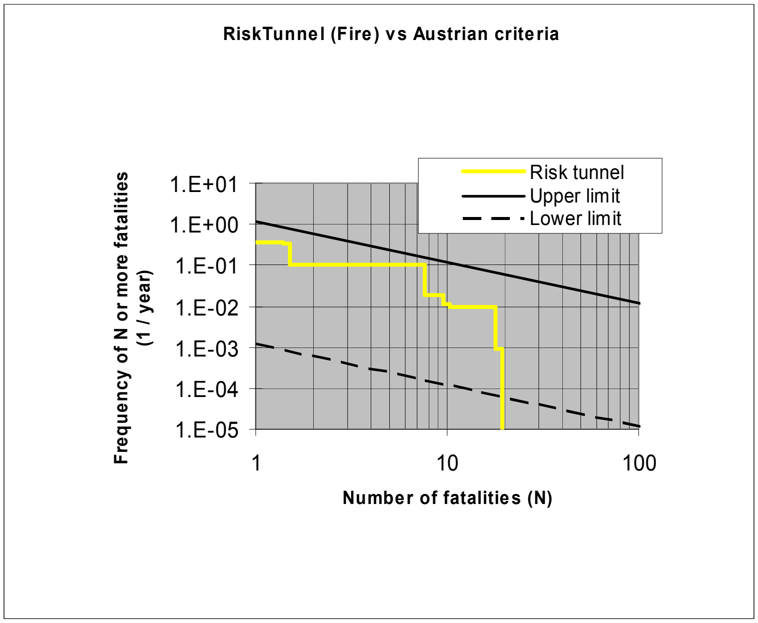


Figure G8

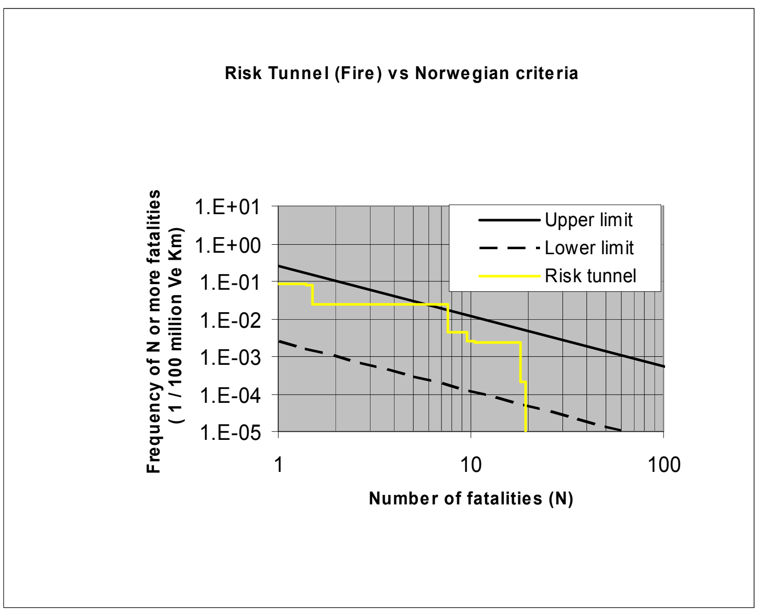


Figure G9