Risk Management in Hvalfjörður Tunnel

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Abstract

This thesis is about how risks in Hvalfjörður Tunnel can or should perhaps be managed. Risk from collisions, vehicle fire and vehicles transporting dangerous goods accidents in the tunnel were quantified by using Probabilistic Risk Analysis (PRA) procedure. Frequencies were estimated using mostly historical data. Models to estimate consequences from these risks were then built by calculating physical effects and measuring their effects on people evacuating the tunnel. Results from the analysis were compared to different criteria. Other ways to make rational decisions regarding risks were discussed. The question on how risks can be decreased or controlled is briefly examined. Finally there is a discussion, both on actual results on risks in Hvalfjörður Tunnel and on the methodology used to quantify these risks.

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Finally I would like to dedicate this thesis to my father and the memory of my mother who have supported and encouraged me throughout my study years but perhaps most importantly, taught me never to give up.

Guðni I. Pálsson
Reykjavík, June 2004

SUMMARY

In Iceland, a road tunnel called Hvalfjörður Tunnel, built according to Norwegian standards, has concerned many from the day it opened. Previous risk analysis for Hvalfjörður Tunnel was carried out without calculating physical effects from fires. These analyses did not include any extensive uncertainty analysis. Over the last few years' research on this subject have addressed many issues; including research on what scenarios can be expected and tools to calculate consequences from these. It is therefore possible to carry out much more advanced risk analysis now than was perhaps possible a few years ago.

In this thesis, collision, fires in passenger vehicles and heavy vehicles and consequences from various dangerous goods accidents were quantified. Uncertainties in values for most variables were incorporated through modelling and by performing a so called Monte Carlo Analysis which resulted in a wide range of results, revealing thus the uncertainty involved. Results from these calculations were interpreted as individual risk and societal risk and then compared to criteria set by the British Health and Safety executive (HSE), Det Norske Veritas and the Norwegian Public Traffic Administration. A new criteria, based on historic levels of traffic accidents, was also proposed but the purpose of that was more to show how a new criteria can be constructed.

Societal risk was only found to be tolerable compared to HSE criteria but unacceptable compared to all other societal criteria. Individual risk was found to be acceptable in 2 out of 4 of the proposed criteria.

Risk was judged acceptable depending on which units were used. If presented in the units per trip or yearly risk, risk could be judged as acceptable but if presented in the unit per travelled km risk was found to be unacceptable.

Criteria to evaluate the acceptability of risk were indeed available but which exactly is the most appropriate one was however not so easily answered. This should perhaps be a task for authorities to work on. It is however obvious risk is rather high and means to lower the risk should be taken. This means also that the Norwegian standard, the tunnel was constructed by, is hardly good enough. These results prove also that future tunnels need to be analysed thoroughly prior to their construction as improving safety in an already built tunnel is likely to be more expensive than if it was planned from the beginning.

The method used in this thesis, sometimes referred as extended Quantitative Risk Analysis or Probabilistic Risk Analysis, proved to be a good tool to evaluate risks in tunnels. However if resources are to be used effectively then risk analysis need to

be complemented with other tools like cost benefit analysis and cost effective analysis.

Different ways to lower the risk were presented briefly but only as a list of different ideas which should be evaluated in the near future. A proposal of how they should be evaluated was however described.

It is recommended that the tunnel owner implements some safety management system to monitor the current risk level and to ensure that all safety features will work when they are needed.

SAMMANFATTNING (SUMMARY IN SWEDISH)

På Island finns en vägtunnel, Hvalfjörður Tunnel, som är konstruerad enligt norsk tunnelstandard. Säkerheten i Tunneln har sedan den öppnades bekymrat många. Tidigare riskanlys för Hvalfjörður Tunnel gjordes utan att ta hänsyn till reel fysik och inte heller omfattande osäkerhetsanalys. Över de senaste åren har kunskapen inom tunnelsäkerhet ökat mycket, inklusive vilka scenario kan ske och verktyg för att beräkna konsekvenser av dessa. Det är därför möjligt nu att göra en mycket mer avancerad riskanlys än kanske var möjligt för några år sedan.

I rapporten kvantifieras risken från vanliga bilolyckor, personbilbränder, lastbilsbränder och konsekvensar från farligt gods oclyckor. Osäkerheter fortplantaredes genom modellering för att få fram alla möjliga konsekvenser. Risk presenteras sedan i form av individrisk och samhälssrisk som jämfördes med kriteria från British Health and Safety Executive (HSE), Det Norske Veritas (DNV) och från det Norske vägverket. En ny kriteria presenterades men mest för att visa hur sådanna kriterier kan konstrueras och vilka principer de måste följa.

Resultaten blev att sämhällsrisken för tunneln bedömdes tolerabel jämfört med HSE men oacceptabel enligt andra kriteria. Individ risken jämfördes med 4 kriteria och i två av dem var den acceptabel. I de fallen när risken bedömdes acceptabel var risken i enheten per trip eller per år men i enheten per rest km bedömdes risken oacceptabel.

Kriteria för att jämföra risk finns men vilken kriteria är mest lämplig blev inte så lätt svarat. Den frågan borde berörda myndigher och politiker arbeta på. Det är dock ganska tydligt att risken är hög och bör minskas. Det betyder också att risken i framtidens tunnlar bör analyseras noggrant innan de byggs for att det är sannolikt att alla ändringar efteråt för att höja säkerheten blir dyrare än åtgärder som planeras innan.

Metodiken som användes, som i bland nämns extended kvantitativ risk analys eller probabilstik (PRA), fungerade bra för att värdera risken i tunneln. Det är dock ganska tydligt att för att använda resurser på ett effektivt sätt, behövs andra metoder liksom kostnads nytta analys och kost effekt analys.

Olika medel för att minska risken i tunnel presentaredes men endast som en lista av olika idéer. Hur dessa idéer kan värderas beskrevs.

För att monitora risken och kontrollera att alla säkerhetskomponenter fungerar när det behövs, rekommenderas att ett säkerhetsledningssystem tas fram.

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1 INTRODUCTION

"It is likely that the unlikely will happen"
Aristotle, 384-322 BC.

1.1 Background

In Iceland, about 30 km north of Reykjavik, there is a single tube sub sea road tunnel called Hvalfjörður Tunnel (length 5,77 km, 165 m below sea level), which connects Reykjavik and the northern and western parts of Iceland, see fig 1. After the Tunnel opened the road between Reykjavik and Akranes shortened about 60 km and between Reykjavik and other communities in the northern and western parts about 42 km.

Figure 1. Map showing Iceland and placement of Hvalfjörður Tunnel.

The tunnel opened in July 1998 and since it opened, the traffic volume has risen to a greater level than ever expected. In the preliminary contract documents the design criterion for the traffic volume (future projection level) was set to 2500 vehicles per day measured in AADT (Annual Average Daily Traffic) with a starting volume of 1500 vehicles per day. In the first whole year of operation, 1999, the AADT was 2800 vehicles per day and in the year of 2002 it reached in excess of 3500 vehicles per day with a peak volume registered as high as 953 vehicles per hour.

According to a fire risk assessment done by the consultant company VST (1999) the fire risk was estimated to lie between tolerable and negligible if compared to British guidance rules used by the British Health and Safety Executive. In October 2002, a group, nominated by the department of justice, assessed the risk of transporting dangerous goods through Hvalfjörður tunnel. Risks were estimated little lower than the consultant VST estimated but following that report, further restrictions on transporting dangerous goods were set in order to reduce the risk from transport of dangerous goods through the tunnel.

These risk assessments regarding Hvalfjörður Tunnel are all presented in a quantitative way but without any effort to reveal the uncertainty in these analyses. Account, for example, where in the tunnel accident occurs has never been considered and only partly what time they occur. The VST assessment is by the consultant regarded as being on the safe side but how much is not known. A thorough uncertainty analysis should give an idea of how certain the risk can be estimated and how much on the safe side previous risk assessments are.

1.2 Aim of the project

The main aim of this project is to investigate risks in Hvalfjörður Tunnel, find out if they can be regarded acceptable or not and if not what can be done to improve safety in the tunnel. This will be done by first looking into previous risk analysis to see what parts can be done better and then carry those parts out in an appropriate way. It is also an aim of this project to investigate the total risk of driving through the tunnel compared to the total risk of driving the alternative road. Investigate if this could be an acceptance criterion for risks inside the tunnel or if there are perhaps other criterion the tunnel should fulfil like the average risk of driving on country roads in Iceland, risk of living in an avalanche area or perhaps something else? Different methods to reduce risk will be discussed and how implementation of such methods may change the risk. Hopefully, this project, will at the end, give some guidance on how the risk management process should look like for other and future road tunnels!

1.3 Method

The methodology used to solve this project can be describe in three steps:

1. Risk analysis
2. Risk evaluation
3. Risk reduction/control

In the first step risks were identified and evaluated in units of frequencies and numbers of fatalities or in other words: What can go wrong? How likely is it and what will the consequences be? In the second step judgements were made on the tolerability of the risk analysis. This was basically done by comparing the risk to various criteria and other comparable risks normally accepted by the society. The last step consists of different ways to reduce and control the risk and methods presented of how decision regarding these ways can be taken.

1.4 Scope and limitations

The project accounts only for safety aspects not health- or environmental aspects. Safety aspects will consider frequencies and consequences from traffic accidents, vehicle fires and accidents involving transportation of dangerous goods. A special attention will be given to all uncertainties in the risk analysis process.

1.5 Structure of the thesis

Chapter 2 describes the general risk management process where different techniques and methods are explained and discussed. Safety systems to monitor risk are also briefly described. Chapter 3 describes the tunnel both historically and technically and previous risk assessments are analysed. Risk in the tunnel is quantified in chapter 4. In chapter 5, risk is evaluated by comparison to suggested risk criteria. Ways and ideas on how to control and reduce the risk is presented in chapter 6 and partly in chapter 2. A discussion on the methods proposed to manage risk is given in Chapter 7 and some concluding remarks and recommendations. The structure of the thesis t is also shown schematically in Figure 2. This figure shows also the proposed risk management process for Hvalfjörður Tunnel.

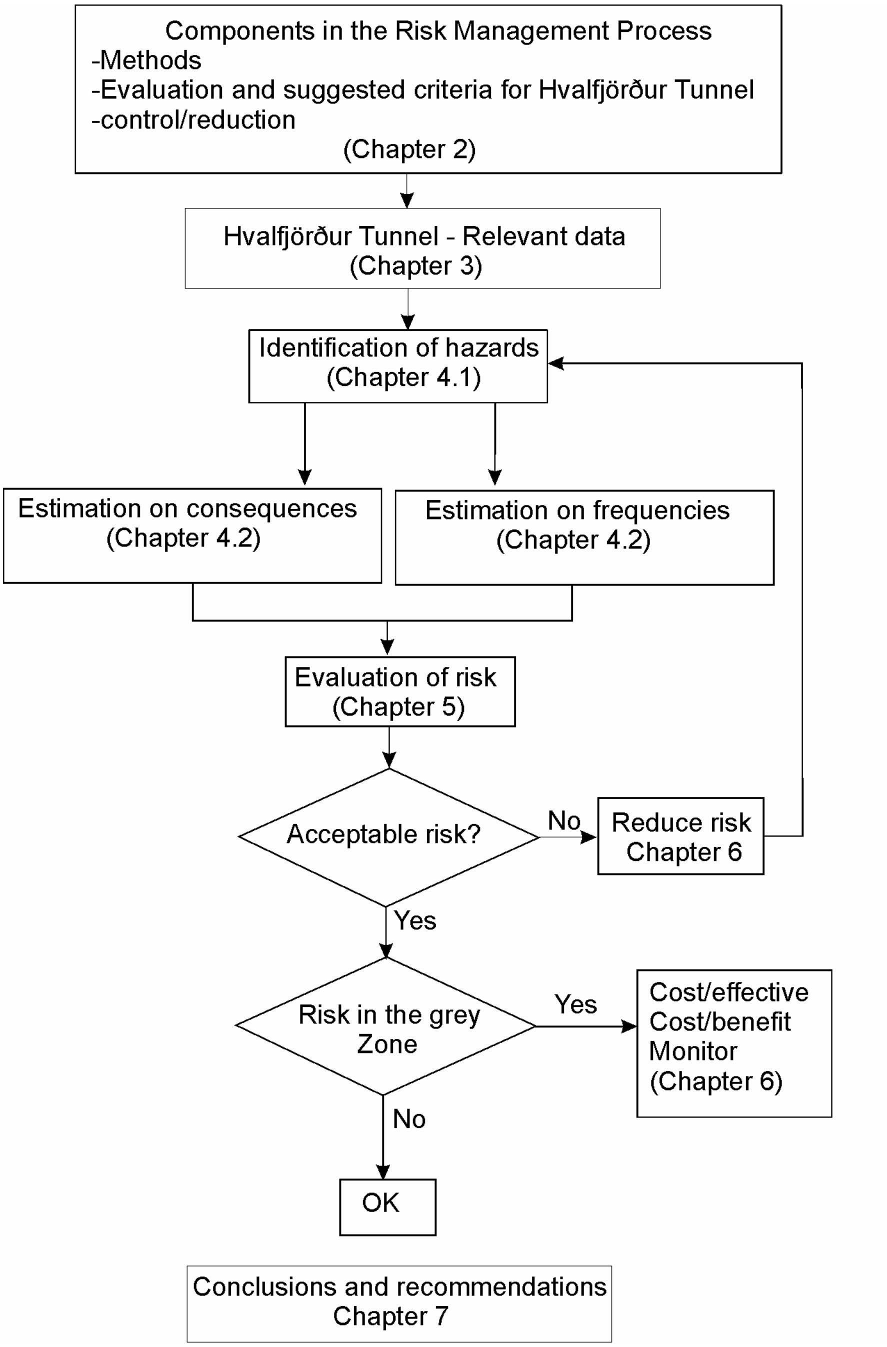


Figure 2. Structure of the thesis and the Risk Management Process for Hvalfjörður Tunnel.

2 THE RISK MANAGEMENT PROCESS

2.1 Introduction

Before introducing the risk management process it is appropriate to start by defining the term *risk*. In many textbooks it is described as the possibility of something bad happening. According to Mattson(2000) it is however possible to distinguish between four meanings of the word, depending on the context:

a) Risk means often danger or threat like if someone would say: “There is a risk for cancer by smoking cigarettes”
b) On the other hand if someone says: “By smoking cigarettes, risk for cancer increases”. Here is risk being referred to increased probabilities.
c) Risk is also defined as the balance of frequency and consequences for a certain event.
d) Risk is also being used to describe the degree of variation. To utilise this better one can think of two companies, A and B. Company A is expecting to sell between 100 and 200 units per month with an expected value of 150. Company B, is however expecting to sell between 140 and 160 units per month with the same expected value as company A. It is indeed logical to say that company A is subjected to higher risks than company B even though their expected values are the same. In other words as the variation in the outcome grows thus bigger the risk.

The risk management process is according to International Electrotechnical Commission (1995), divided into three steps:

1) Risk analysis
2) Risk Evaluation
3) Risk reduction/control

Definitions on these terms are as follows:
Risk analysis is a process for a given system which includes identifications of threats, assessment of these threats and judgement on them. Risk analysis methods can be divided into two groups, qualitative and quantitative methods. Qualitative methods include keywords like large, medium and small without any attempts to specify further the probabilities. This form is especially useful to screen out which scenarios need to be analysed closer. In quantitative methods like QRA (Quantitative Risk Analysis) an estimation of probabilities and consequences is given numerically. In both qualitative and Quantitative analysis the analyser tries to give an answer to the following basic questions, which indeed are often used to define the technical meaning of the term risk (same as point c) above):

- What can go wrong (what scenarios can be expected)?
- How often will it happen (frequency)?
- If it happens what will the consequences be?

Risk evaluation is the process when the risk analysis is completed and results are being compared to appropriate criteria. Decision on weather the risk can be regarded ad acceptable/tolerable or not are made. Alternatives are also analysed here.

Integration of the first two steps is often referred to as *risk assessment*.

The final step in the risk management process is where final decision on what and how preventive measures are implemented to reduce or control the risk.

All three steps are summarized figure 2.

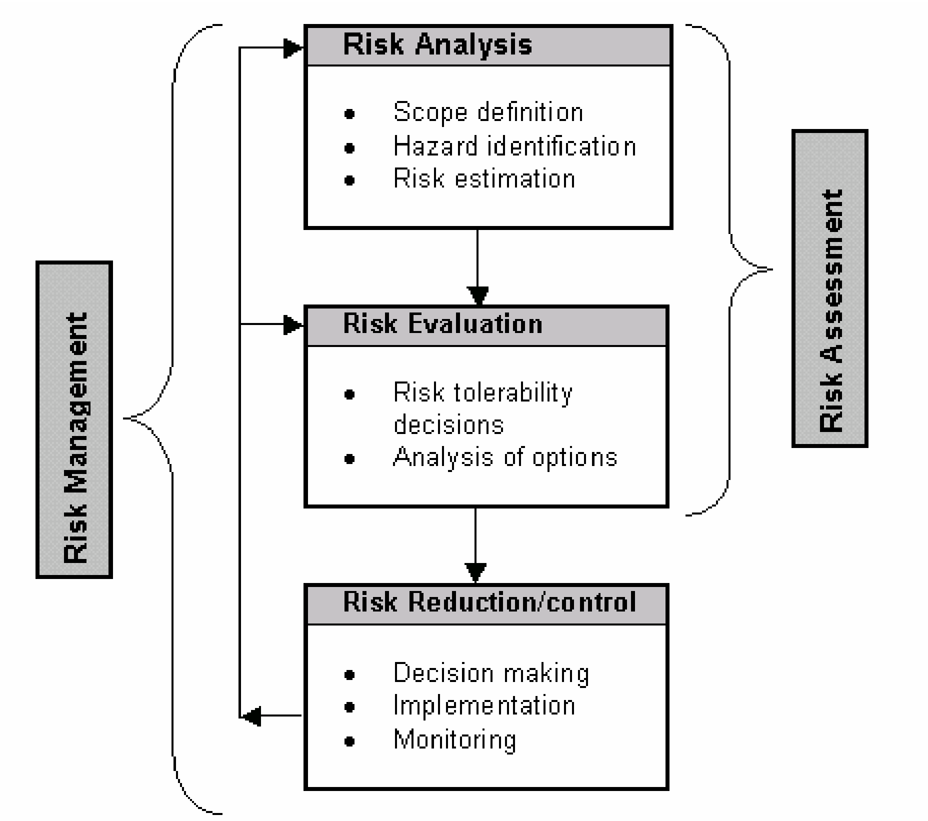


Figure 3. Flow chart for risk management (International Electrotechnical Commission, 1995).

2.2 Risk analysis methods

Sources of risk are often divided into classes depending on their character and origin:

- Technological risks
    - Industrial factories, transportation systems, chemicals
- Nature risks
    - landslides, flooding, strokes of lightning,
- Social risks
    - Sabotage, terrorism

To identify possible threats there are a number of methods available. The spectrums of these methods are shown below in order of increased advance and complexity.

Preliminary analysis HazOp What if Checklists Risk matrices	**Qualitative**
Index Risk matrices Consequence analysis	**Semi Quantitative**
QRA (Quantitative Risk Analysis) also sometimes referred as PRA (Probabilistic Risk Analysis)	**Quantitative**

In this thesis preliminary analysis and quantitative methods were used and therefore only these methods will be further described.

2.2.1 Preliminary analysis of possible threats

In the early stages of a risk analysis process this method is often used to identify and give a rough idea about the frequency and consequences from various risk sources. The purpose of this method is often to screen out risk sources that don't need further evaluation. Flooding in a sub sea tunnel might for example not need further research if experts in the field have concluded that the probability for flood inside the tunnel is extremely low, perhaps equal to a meteor falling from the sky into the sea above the tunnel. It is however necessary to document thoroughly why some hazards don't need further research to show that hazards have been identified but have been excluded due to rational reasons. This method is therefore simple and robust as it can be based on dialogue with experts in the relevant field and helps the analyser to choose which risks need further evaluation.

2.2.2 Quantitative Risk Analysis methods

In reality almost all data that are used to quantify risks are subjected to some degree of uncertainties. Traffic density in a certain road segment might for example vary from zero to 100 vehicles passing per hour. Using the absolute worst case scenario values for example in a model to describe the amount of fatalities would lead to an extremely conservative result. Such results might be so unlikely that they might even be disregarded. Therefore it is often appropriate to use the worst likely value, say 80-95 percentile of the absolutely worst case value. Sometimes average values are found to be appropriate if the analysis is intended to represent the average risk. It is therefore important to document thoroughly which values are used to represent this risk, to be able to say if the results are conservative or not. As a good practice all such choices should be complemented with an uncertainty analysis.

In a more advanced form uncertain values are assigned density distributions to represent all possible values and their likelihood. This results therefore in a distribution that describes all possible consequences and frequencies for the risk, thus revealing the uncertainties involved. Figure 4 describes how this works.

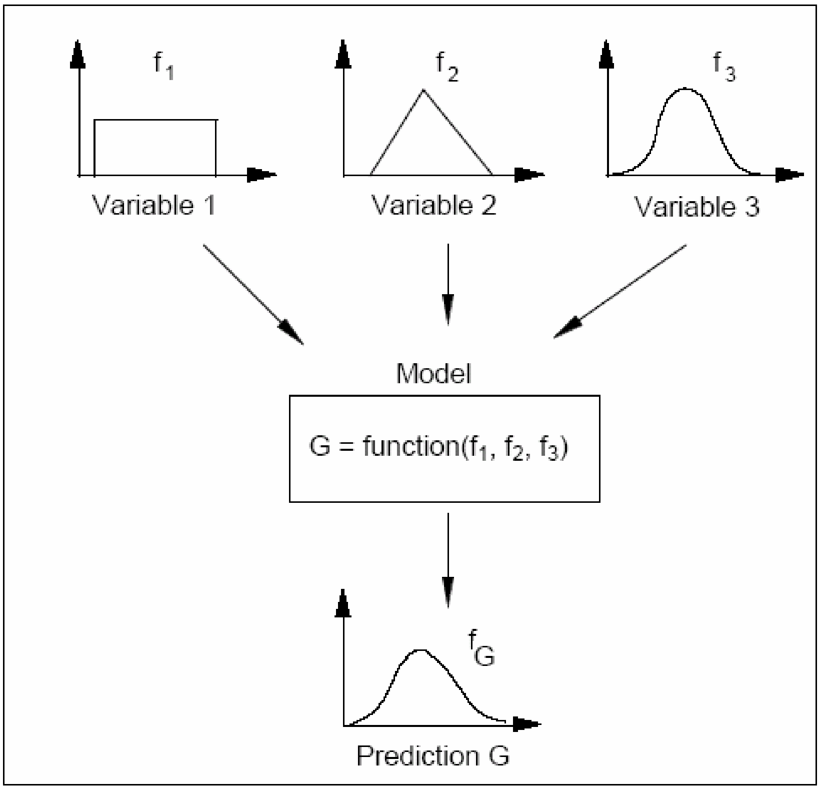


Figure 4. Propagation of uncertainy through a model (Frantzich, 1998)

To solve mathematically joint distributions is possible but extremely time consuming and complex. A techniqe called *Monte Carlo Analysis* (sometimes Monte Carlo Sampling) is therefore often used to solve problems of this kind. In a Monte Carlo analysis, numbers for each variable are generated randomly according to their respective distribtuion and the outcome calculated each time. Each time numbers are generated and an outcome calculated is referred to as one simulation. To get the spectrum of all possible combinations, especially extremes, numbers of simulations, typically 10,000 or even more simulataions are needed. In this thesis the software @RISK, version 3.5 from the Paliside corporation, was used to handle the Monte Carlo analysis

2.2.3 Tools to assess frequencies and probabilities

2.2.3.1 Fault and event tree analysis

The purpose of doing *fault tree analysis* is to gain knowledge about which basic elements are causing the failure to occur. This is done in a logical way so that the frequency for the event can be estimated. Figure 5 shows how a typical fault tree looks like.

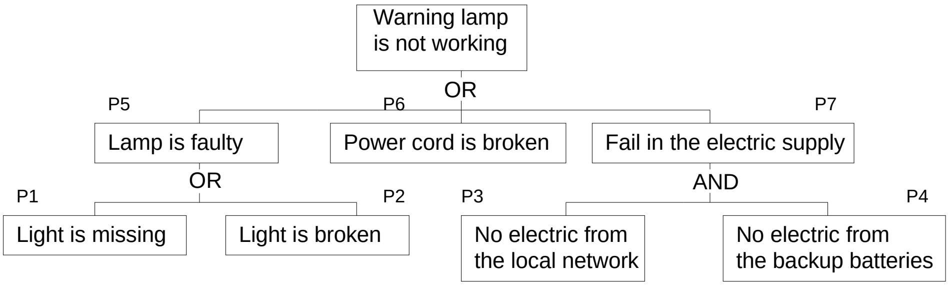


Figure 5. Fault tree, adapted from Mattson(2000).

In a simplified form, top events are calculated by adding components that are associated with the logical term “OR” but multiplied if the are associated with “AND”. In the figure above the frequency or probability for a warning lamp not working would be calculate as follows: P5+P6+P7=(P1+P2)+P6+P3*P4.

An event tree analysis is the opposite to the fault tree analysis because instead of finding root causes, the purpose is to find possible outcomes from the initial event. For evaluation of possible outcomes from a fire, for example, event tree analysis can be useful. Figure 6 illustrates a typical event tree for a fire scenario. Numbers shown are fictional.

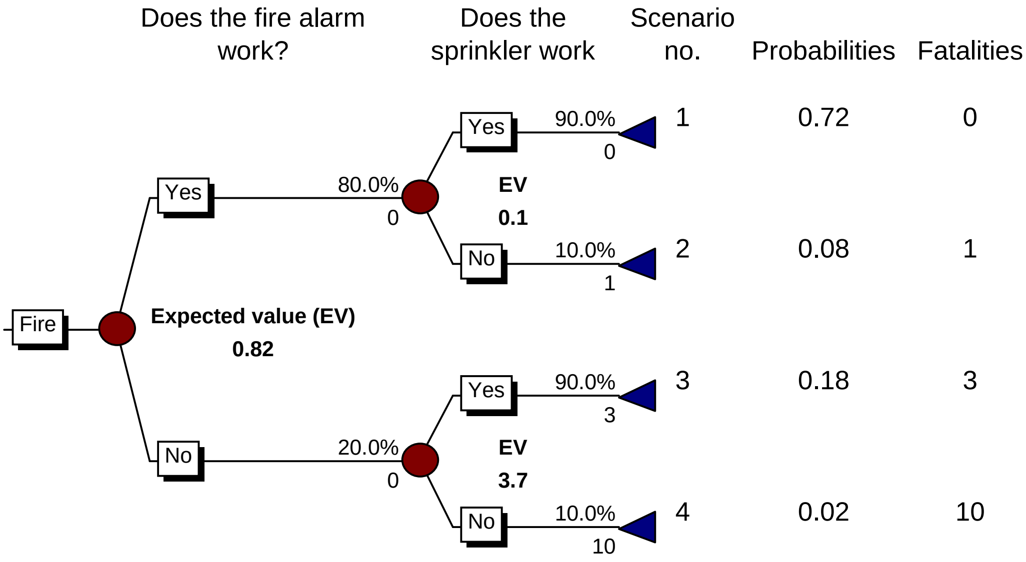


Figure 6. Event tree for a fire.

More information regarding the fault tree and the event tree can be found in CCP (2000).

2.2.3.2 Historical records with Bayesian updating

Assessment of frequencies or probabilities can be achieved in many ways. Using historical data is probably the most forward and natural choice. Using historical records is however not always easy because records for some events might be insufficient and sometimes incomparable because local conditions might deviate from those where the generic data was collected. Changes in systems are also not being reflected by using historical data. Using expert judgement is therefore often the only choice the analyser has unless Bayesian updating can be used, which is a method that joins subjective judgements with objective facts.

In every day life people use Bayesian updating without knowing it. Imagine an observer sitting in a restaurant wondering about the probability for a female to be the next guest walking into the restaurant. Having no other information it would be reasonable for the observer to estimate 50% chance for a female to be the next guest. If the observer however knew that a feminist convention was being held near to the restaurant then it would be reasonable for the observer to estimate the probability for the next guest to be female to be higher than 50%. Principally then this is simply what Bayesian updating is all about. New information is being used to improve prior probabilities to estimate posterior probabilities.

Tunnels are different in shape, length and lightning and drivers using the tunnels might have varied driving skills et cetera. Fire frequencies in tunnels can therefore be expected to vary a lot between different tunnels based on those various factors. Trying to build a model to account for factors controlling the fire frequency is obviously almost impossible. Using the Bayesian technique makes it however possible to do a a priori estimation on the fire frequency based on historical experience in other tunnels which then can be improved to estimate posterior probabilities as new information regarding the fire frequency in the actual tunnel are gained. Uncertainty regarding the fire frequency should also decrease with time as the technique accounts for the weight of the information.

Information on how to calculate Bayesian updating can be found in almost every basic statistical text books.

2.2.4 Estimation on consequences - effect models

Consequences in risk analysis can be given in many different units, such as number of fatalities, serious injuries, loss of money et cetera. What units are used depends probably mostly on for whom the risk analysis is being conducted. Companies would preferably like to know how much money they might loose while official authorities are more concerned in numbers of fatalities.

One way to estimate fatalities for certain events is to use historical records for similar events. This is however not always possible as often one is trying to measure effects from rare events and often at unique circumstances. Another way when historical records aren't available is to simply find or construct a model to calculate physical effects and the effect on people.

Models to measure physical effects are often based on mathematics and the general laws of physics. Model to measure what certain physical effects have on humans are mostly based on so called dose - response tests which predict at which dosage death or severe injuries can be expected. Dose - response models are mostly based on animal tests where animals are given increasing dose until severe injuries or death is detected. The threshold at which the dose causes no response is also registered. The dose-response curve is then extrapolated to humans.

In situations when time, money, tools or knowledge aren't available to construct complicated models or do a survey to estimate consequences there is still one tool available, namely using one's owns judgement. Best practice is to use judgement from experts in the relevant field. This tool can be very powerful and effective as it is possible to come relative quickly to some conclusions. All reasons, whatever they are, should however be documented as accurately as possible since the method is not about guessing. This tool is mostly used in qualitative risk analysis but sometimes as a small part of a quantitative risk analysis.

2.2.5 Sources of uncertainties

Above mentioned methods, both frequency/probability and consequence methods are evidently subjected to many uncertainties. Summarizing these it is evident that they can be classified into at least two categories, aleatory and knowledge based uncertainty. Aleatory (stochastic and/or randomness) is found everywhere in nature like weather conditions, (velocity of wind, temperature et cetera). This variation or uncertainty can not be reduced. Models today are not yet so sophisticated that they can describe the reality 100% but they (or should at least) tend to get better with better knowledge. Knowledge based uncertainty can thus be reduced. Another source of uncertainty which should be mentioned is calculation errors which can be linked to both numerical errors and human errors. Calculation errors are more likely to occur as the complexity of a problem increases.

2.3 Evaluation of risk

Evaluation of risk includes the process where risk is being measured against some criteria so that one can conclude if the risk can be regarded negligible, acceptable, tolerable or in the worst case unacceptable. This process involves also evaluation of other choices under consideration.

2.3.1 Few Principles regarding risk criteria

In modern society with all its activities it is clear that people are willing to accept risks up to a certain degree. People are therefore not willing to spend countless amounts of money in order to decrease risks. Following these facts 4 principles have been set to give decision makers a starting point in evaluation of their risk (Davidsson, Lindgren, Mett, 1997).

1. **Practical**
   An activity should not include risks that can be decreased or eliminated with reasonable means.
2. **Proportional**
   The total risk an activity results in should be proportional to the benefits it brings.
3. **Distributional**
   The risk should be distributed as evenly as possible amongst the society in relation to the benefits the activity brings. This means that some individuals or groups should not bear risks that are not in proportion of the benefits they receive from the activity.
4. **Avoidance of catastrophes**
   It is better to have frequent accidents with small consequences which the rescue services can handle rather than infrequent and large consequences.

2.3.2 Risk Perception

How do people perceive risk? Does the way people perceive risk affect their acceptability of risk?

Perception was in the beginning of psychological researches associated with how the human body perceives the environment through it's vision, hearing and other body sensor. These studies have revealed that people learn mostly through experience. How people perceive risk is learned in the same way, through experience, either real or through some media.

According to the Royal Society (1992) then risk perception involves peoples faith, attitude, judgements, feelings and social and cultural judgements that people associate with risk and their benefits. How risk is presented affects also how people perceive risk. To exemplify this we might think we have to choose between A or B:

A: 200 out of 600 were killed
B: 400 out of 600 survived

Most people would choose B as it sounds better even though both alternatives include the death of precisely 200 people.

Survey by Fischoff et al. (1981) showed that people tend to underestimate ordinary risks like dying in cancer or in a traffic accident while the risk of dying in flight accident and other unusual risks are overestimated. This means in other words that certain activities may be judged as more risky by the public then objective evaluation might do.

Negative versus positive factors controlling the risk perception are for example:

- Involuntary-voluntary
- Not known-known.
- Catastrophic accidents are possible-catastrophes not possible
- Uncontrollable-controllable
- Benefits from the activities are small- benefits are high

Comparison of above factors reveals why flying is often perceived a lot more dangerous than driving even though objective analysis has revealed that flying is much safer than driving. People do however take the chance of flying, mainly because of all the benefits.

Slovic, Fischoff & Lichtenstein (1980) studied different factors and concluded that three independent factors control how people perceive risks. Figure 7 shows two of those factors.

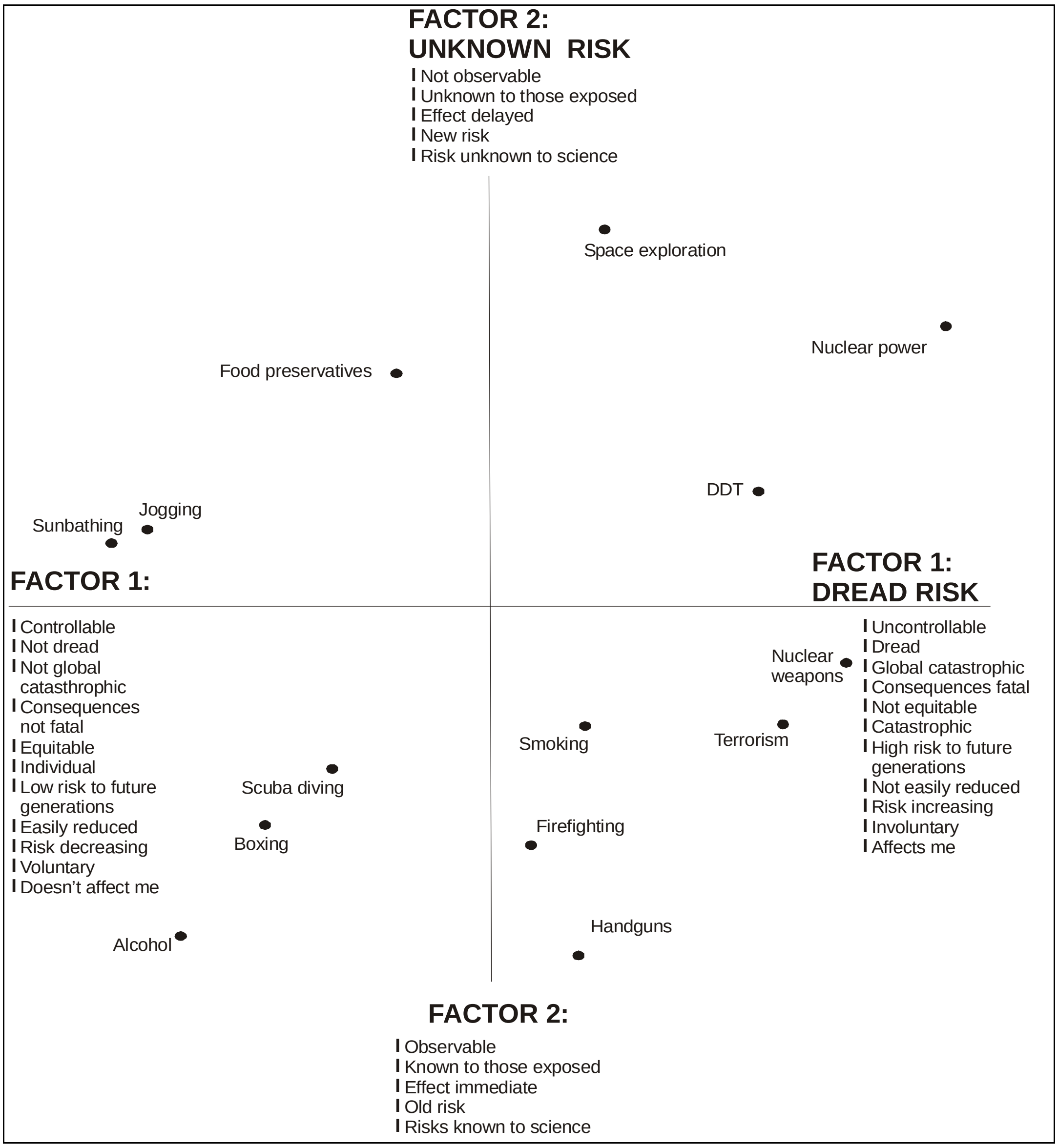


Figure 7. Factors controlling peoples perception on risk. Simplified figure from Slovic, Fischoff & Lichtenstein (1980).

Road Tunnels are probably situated close to the centre in the upper right corner but a survey is however needed to conclude if that is the case.

2.3.3 Individual risk

The purpose of measuring individual risk is to secure that individuals in the society are not exposed to unacceptably high risks. Individual risk is usually defined as the probability of being killed over certain exposure time, normally as per year. In traffic risk is however often given as fatalities per vehicle km or as per person km. The relationship between those two is simple; a vehicle driving total 100 km with 2 persons corresponds to 100 vehicle km but 200 person km. In flight, risk is also sometimes given as per trip because flying involves so many person km and the number of flight accidents depends mostly on amounts of landing or take off, not travelled km.

Average individual risk is often calculated from historical data like: number of fatalities per year divided by the number of persons exposed to the risk.

Place specific risk is the risk of a person dying which is hypothetically exposed continually to the risk.

When account is taken of the fact that an individual is not continually exposed to the risk then one is referring to *individual specific risk*. By using this definition makes it possible to compare different risks like driving a vehicle, flying, working et cetera.

As anyone can see, there are different definitions on individual risk. It is therefore extremely important to be careful that similar definitions for the individual risk are being used when comparing individual risk to other risk or criteria. Another important thing to remember regards which units are being used because different units for the same risk can give totally different perception of the risk. In general it can be said that comparison of risk is not an easy task and there are a number of factors that need to be considered.

2.3.4 Societal risk

The purpose of societal risk criteria is to limit the risk for local communities or the whole society. Expression for societal risk give much more detailed information about the risk character than individual risk because expressions for societal risk present how many fatalities can be expected every year and/or how many fatalities might be expected in a single event.

Societal risk can be presented in a so called FN curve which stands for **F**requency of accidents versus **N**umber of fatalities. It is important to notice that FN curves show the relationship between the accumulated frequency for N or more fatalities. The main benefit from using FN curve is that they clearly show the risk of having many fatalities in a single accident which individual risk does not, do.

Statistically expected number of fatalities per year is also another expression for the societal risk. Using this number gives an idea of how many lives might potentially be lost per year on the average. A potential loss of life equal to 1 per year might for example represent an accident expected to occur every 100 years with the consequences of 100 fatalities. This number is also sometimes called PLL (Potential Loss of Life).

Criteria to compare FN curves can be constructed in few different ways. One is to use historical data. Such criteria would then reflect the will of the society to retain the current risk level in the society. Another way to construct criteria for FN curves is to start by deciding the frequency for N= 1 or more fatalities. This number might be the average fatality rate per driven vehicle for example. The next step would be to decide the slope for the curve. The slope is usually given by exponent. Typical exponents are –1 and –2. This means for example that if N=1 that the frequency for N=10 must be 10 times lower if the exponent is –1 or 10^{-1}. Using exponent of –2 would mean that the frequency would have to be 100 times lower or 10^{-2}. Examples of a FN curve and different criteria are shown in Figure 8.

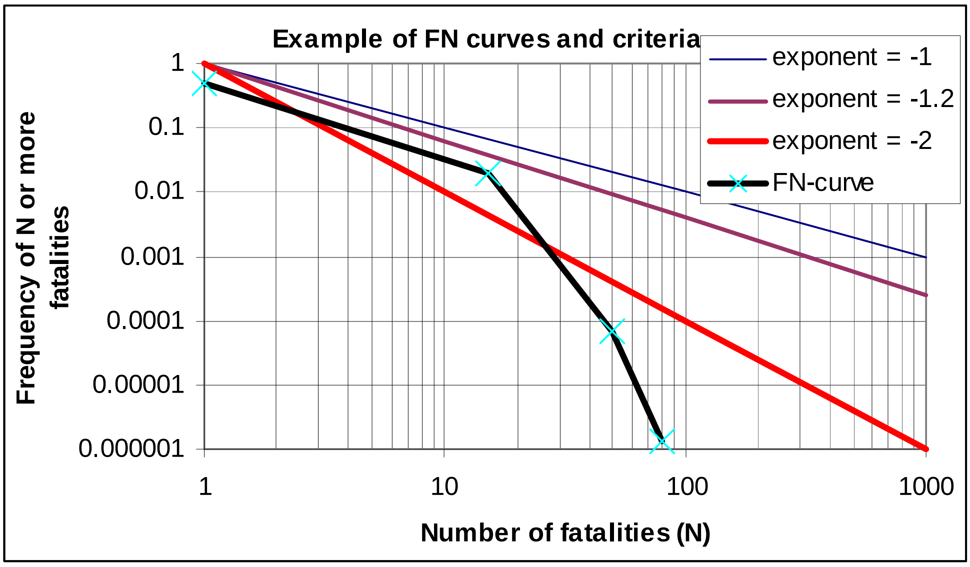


Figure 8. Example of different criteria compared to FN curve.

Because the criteria represent the accumulated frequency for N or more fatal accidents, using slope less than -1 represents the societal aversion against large accidents.

2.4 Risk reduction/control

Once the risk assessment has been performed there might be few alternatives to choose from. Choosing the alternative including the least risk is not always reasonable due to high cost for example. How to make rational decisions is therefore important. If the risk assessment shows that the risk is acceptable it follows that all components in the system must be maintained to ensure the same level of risk. To help those in charge maintaining the same level of safety, some kind of a management system might be necessary.

2.4.1 Decision making

In essence, risk analysis is, or should at least be, about making informed decisions (Kammen, Daniel M. and Hassenzahl David M., 1999). Before rational decisions can be made the problem must be well stated and the risk analysis must be transparent.

It is also important that the right owner of the problem accepts it as his problem to solve. From the companies viewpoint the focus is usually on the profit, goodwill, regulations and not on the whole society. In other words activities that don't benefit the company in some way are usually not done. Banning transportation of dangerous goods through Hvalfjörður tunnel might for example benefit the tunnel owner due to lower insurance cost but the benefit for the society might be negative due to higher transportation cost, more accidents, more oil consumption more pollution et cetera. This is however possibly not the best example because this measurement might possibly benefit the society as well but that hasn't been analysed. Decision regarding which vehicles are not allowed to travel through the tunnel are also made by the Police unit in Reykjavik, not by the owner of the tunnel!

Mattson (2000) has through literature study found out that different decision tactics can be grouped into four main categories:

A. Technology based criteria
    - "Always use the latest available technology"

B. Rights based criteria
    - Zero risk approach
    - Decrease the risk until it is less than 10^{-x}

C. Benefits based criteria
    - Cost Benefit analysis
    - Cost effective analysis
    - Multi attributive benefits

D. Hybrids of B and C

According to the *technology criterion* one should always use the best and latest technology available. In a world with constantly improving technology this criterion can easily lead to enormous waste of resources as one would constantly have to invest in the latest technology available.

Using the *zero risk approach* means setting a goal where risks in the future have been totally eliminated. This has been done for the traffic in Sweden and is in the debate also in Iceland. Saving the last live in traffic will, as anyone can imagine, cost enormous amount of resources which might definitely be used more effectively elsewhere in the society.

Decreasing the risk until it is smaller than 10^{-x} using individual risk and societal risk (FN curves) has the main advantage that results are easy to understand and decision can quickly be made based on these criteria. Disadvantage of using these methods is almost the same as in the zero risk approach, the marginal cost of saving the last life in order to lower the risk beneath 10^{-x} can cost enormous amounts of money which might save more lives if used elsewhere in the society. Resources are in other words not being used as effectively as they perhaps might.

In a *Cost benefit analysis* (CBA) all societal cost against all benefits are compared. According to CBA, if the sum of all benefits is higher then the sum of all cost for a certain project then the well being of the society should increase and the project should be implemented. This has to be done in monetary unites and traditionally, economic units are often used. This means that value for the human lives and other things that don’t have exact marketing values must be estimated. These estimations are usually associated with many uncertainties and they are usually not easily obtained. This involves also many ethical problems like are older persons less worth than younger ones? These kinds of ethical problems are not found in the rights based criteria because risk is the same for everyone exposed regardless of their age, sex et cetera.

In a *Cost – effective* analysis (CEA) the goal is to choose that alternative which gives most effect in proportion to the cost. Using this method says unfortunately nothing about if certain alternative benefits the society or not, only what alternative results in the biggest impact in proportion to its cost. This method is however very useful for authorities having a certain amount of resources in order to help them spend those resources in the most effective way.

Using Hybrids of B and C is often used if the risk is for example in the ALARP zone. Mattson (2000) criticised this by wondering why should one suddenly use CBA if the risk is little higher than a certain level and not if the risk is little lower. It should be possible to use the CBA regardless of the current risk level. Risk analysis serves however another important feature, namely to identify hazards and evaluate them. Models used in such analysis can also be used to measure effects from certain measurements, in other words they can provide the appropriate data to perform CBA and CEA.

2.4.2 Implementation and monitoring

There are basically two strategies available to control risks; reactively or proactively. By controlling risk reactively one waits for an accident or incident to occur before any risk reducing measures are implemented. Thinking proactively means that available preventive measures are implemented in order to either reduce the probability for an accident or to reduce possible consequences from an accident. Risks are also monitored constantly to ensure safe operation. Thinking proactively has become more and more important because in a dynamic environment, hazard sources, their control, requirements and sources of disturbances change frequently. To be in control in high risk organisations there must exist some kind of a system that ensures that risks are under control. Such systems fortunately do exist and are widely used in the chemical process industry. A good reason for why organisations should adopt safety management systems is the fact that studies have shown that the most common reason for accidents can be related to failure in the management and implementing management systems should reduce the possibility of such failures.

Systems for safety systems are similar to quality management systems like ISO 9001. Systems intended especially for safety questions are often a part of other systems for example the SHE (Safety, Health, Environment) system proposed by Kemikontoret (The Association of Swedish Chemical Industries) and BS 8800 (British Standard “Guide to Occupational Health and Safety management systems”).

By implementing a system to tackle risks will have the extra benefit of increased credibility of the organisation involved amongst the working staff, authorities, people living in the neighbourhood, mass medium and the general public. This credibility might become extra valuable in a time of crisis.

A safety management system includes in few words the following points (Kemikontoret, 1996)

The structure of safety system should include the following points:

- Policy
- Routines
- Instructions

A Policy states the vision and objectives of the company. Routines should give simple and clear information and instructions about what needs to be done, when, where and by whom. Typical heading in a work routine are:

- Objective
- Scope
- Principe rules and methods
- Responsibility for the routine
- References

For a safety management system to be successful there are a number of important points to consider:

- The implementation of a management system must have clear support from the top leadership.
- The executive manager must go out amongst the staff and speak for the system
- Engaging the staff in building up management systems is important. The staff must feel that their points of views mean something. The aim of a safety management systems are also about to engage the staff in terms of risk or in other words producing culture where safety is of primary concern.

3 THE HVALFJÖRÐUR TUNNEL –RELEVANT DATA

3.1 Short history of the tunnel

Crossing the fjord Hvalfjörður used to involve the use of a road with many turns and slopes. It was also regarded as a dangerous road by the public as it had cost many lives. According to statistics from Vegagerðin (The Public Road Administration) covering the year 1993-1997, the road was however as dangerous as other roads in the rural road system per kilometre, but as a section in the road system compared to other sections it looked worse because it covered additional kilometres.

Crossing the fjord with a sub sea tunnel had been in debate for decades before it came to reality. A committee nominated by the administration of transportation in Iceland first published the idea in a report in 1972. It indicated that it would not be profitable. In 1987, however, the department of road administration published a report, which indicated that it would be profitable to build a sub sea tunnel and further research began. In 1991 a company, called Spölur, was founded to work further on a sub sea tunnel and in 1996 the tunnel work began. The tunnel opened for traffic two years later, in July 1998, and has been in operation since, without any major accidents.

Before the tunnel opened it was assumed that the payback time would be approximately 20 years but because of huge increase in the traffic volume it is expected to take a lot shorter time. The tunnel is supposed to be handed over to the state when all loans have been paid up.

3.2 Technical data

The structure:

- Total length of the tunnel is 5770 m thereof are 3750 m under sea.
- In the southern part there is one lane for each direction. This segment of the tunnel is 3600 m long.
- In the northern part there are however two lanes for vehicles travelling north and one lane for vehicles travelling south. Total length of this segment is 2200 m.
- The slope in the south part ranges from 4-7% while slope in the north part is 8.1%.
- Deepest part of the tunnel is 165 m below sea level.
- Maximum sea depth in the fjord over the tunnel is 40 m.
- The rock above the tunnel is at least 40 m thick.

<u>Safety equipment</u>:

- A toll, portal and control room is situated 330 m from the northern tunnel portal. All equipment is operated from the control room which is operated 24 hours.
- Interval between emergency phones, directly connected to SOS 112 is 500 m. Tunnel operators can see from which emergency phone a call is being made, thus knowing where help is needed.
- Emergency lay bays are situated with 500 m intervals. Three of those are especially for larger vehicles.
- At both portals there are traffic lights and a physical barrier, controllable from the control room.
- GSM phones can be used inside the tunnel to call SOS 112.
- Tetra communication system for the rescue services is usable inside the tunnel and outside the tunnel as well.
- 32 fans in 4 groups are situated in the tunnel. They can be controlled from the control room to blow in preferred directions at varied velocity. To maintain air quality, fans are controlled according to the below criteria:
    - If level of CO_2 and CO increases above a certain value, fans automatically turn on.
    - If CO_2 level gets higher than 100 ppm, all fans turn automatically on.
    - If CO is above 100 ppm for over 15 minutes the tunnel shuts automatically.
    - It is possible to turn off automatic control of fans in the control room.
- Natural draft is from north to south due to geothermal activity in the southern part. Wind inside the tunnel varies according to outside weather, traffic and velocity of fans. Wind inside the tunnel can vary from 0.1 m/s to maximum 2.5 m/s if all fans are blowing at maximum velocity.
- Message through radio can be sent through three radio channels
- A water reservoir is situated in the bottom of the tunnel. 4 pumps operate in shift to pump water out of the tunnel. It is possible to pump 2000 litres/min from that reservoir into the tanks of fire rescue service vehicles.
- It is estimated that the fire brigades from Akranes and Reykjavik will arrive at Hvalfjörður Tunnel, 20-30 minutes after request of their assistance has been made.
- A hydrant is situated less than 1 km away from the northern portal. At the south portal there is a 7000 litre water tank.
- The number of vehicles inside the tunnel is monitored through a vehicle counter, counting vehicles going in and out.
- Velocity cameras are inside the tunnel. They are operated by the police department in Reykjavík.
- Steel barrier at both sides stops vehicles higher than 4.2 m to enter the tunnel .
- All equipment in the tunnel is maintained regularly according to a maintenance handbook. A handbook to maintain safety equipment exists and certain parts are checked weekly.
- The transport of liquefied petroleum gas in a quantity of 50 kg or more is always forbidden.

- The transport of dangerous goods is forbidden during certain times when traffic is higher than normal.
- Maximum allowed vehicle velocity is 70km/h.

3.3 Traffic data

Spölur charges vehicles for driving through the tunnels according to four classes based on their length and type:

Class 1.	Vehicles shorter than 6 m in length, typically passenger vehicles
Class 2.	Vehicles larger than 6 m but shorter than 12 m in length, typically vans and small trucks.
Class 3.	Vehicles larger than 12 m en length, typically larger trucks.
Class 4.	Motorcycles.

Information on numbers of trips through the tunnel were obtained from Spölur, see Table 1.

Table 1. Traffic in Hvalfjörður Tunnel, number of vehicles travelling through the tunnel. (*Year 2003 includes only traffic until 1. August.)

Year	Class 1	Class 2	Class 3	Class 4	Total traffic
1998	405,872	13,259	10,787	686	430,605
1999	954,955	31,197	25,381	1,614	1,013,147
2000	1,044,760	31,808	30,665	1,651	1,108,884
2001	1,161,172	34,764	35,131	1,633	1,232,700
2002	1,215,878	34,641	40,243	1,390	1,292,152
2003*	810,585	23,094	26,829	927	861,435
Total	**5,593,223**	**168,763**	**169,036**	**7,901**	**5,938,923**
%	**94.18%**	**2.84%**	**2.85%**	**0.13%**	**100.00%**
Veh. km	**32,272,895**	**973,764**	**975,338**	**45,587**	**34,267,584**

Note that majority of all vehicles entering the tunnel are passenger vehicles (94%) and the rest are larger ones. The amount of passenger vehicles was taken as the sum of classes 1 and 4 and the amount of heavy vehicles as the sum of classes 2 and 3. Figure 9 shows the development in traffic since the tunnel opened. Clearly there is a trend for growing traffic but any speculation on future traffic is a demanding task which is not one of the objectives of this thesis. AADT stands for Annual Average Daily Traffic.

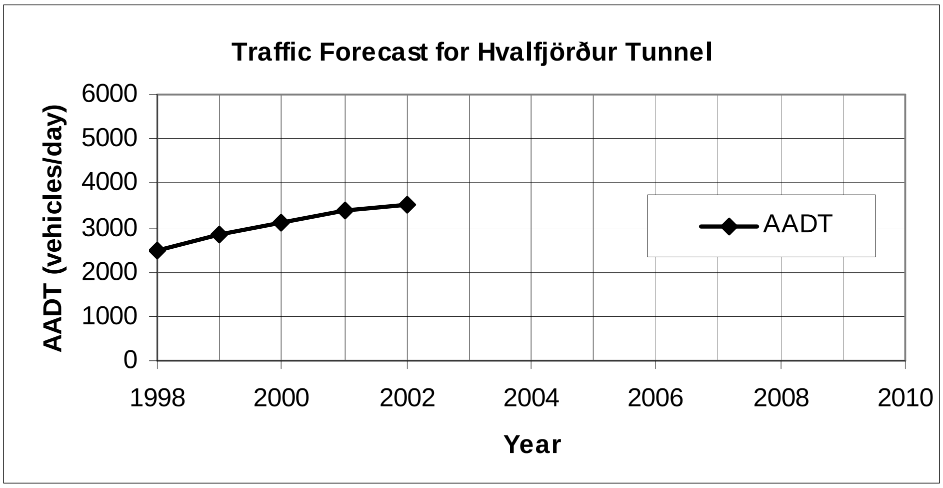


Figure 9. Traffic forecast for Hvalfjörður Tunnel.

Vegagerðin (The Public Road Administration) operates a traffic counter in the middle of the tunnel which counts the number of vehicles passing through the tunnel over periods of 15 minutes. Data for the whole year of 2002 was obtained from Vegagerðin. This data is very valuable because the traffic varies greatly depending of time of day and seasonally (winter or summer). To give some idea about how much the traffic varies a graph showing the probability for the number of vehicles entering the tunnel over a period of 15 minutes was constructed, see Figure 10. From the figure it can be seen that on average the total traffic is about 32 vehicles while the average traffic when transport of dangerous goods is allowed is 50% less or 16 vehicles. It can also be seen that traffic over 15 minute periods is varying from zero to as high as 250 vehicles.

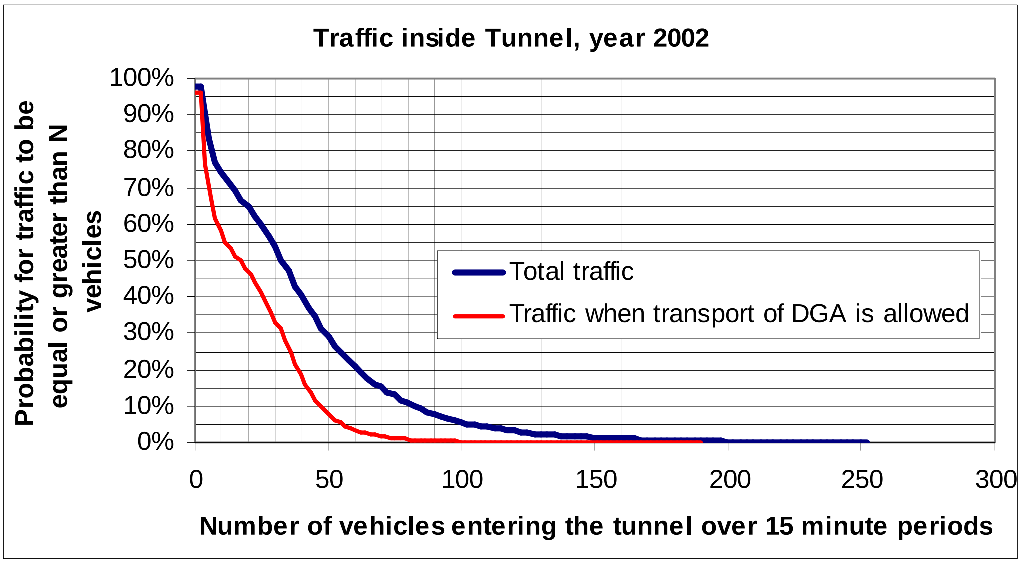


Figure 10. Density distribution for traffic in Hvalfjörður Tunnel.

Assuming that fatalities in accidents like fire is strongly dependent on the number of people exposed it's obvious that the uncertainty is bound to be great. Difference between the average scenario and the worst case scenario might be multiplied by a factor 250/32 = 15. Figure 10 gives therefore an indication of what uncertainties are to be expected.

3.4 Review of previous risk assessments for Hvalfjörður Tunnel

3.4.1 VST Fire Risk assessment

The VST Fire risk assessment, dated March 1998 and revised 1999, was done by using a Quantitative Risk Analysis (QRA) procedure. The structure of the VST report is as follows:

Terminology, risk measures and acceptability criteria
1.0 Introduction
2.0 Fire Hazards
3.0 Analysis of Fire Consequences
4.0 Assessment of fire probabilities
5.0 Risk Calculations
6.0 Risk Reduction
7.0 Summary

The acceptability criteria used in the VST report is taken from the Health and Safety Executive in U.K (HSE). The VST report points out that this criteria was constructed to be used for large industrial activities like nuclear power stations. The VST report states further that the negligible levels are conservative having in mind that no individual has to bear unfairly high risk from the tunnel and that the whole population can share the benefits from it.

Comments:
Considering the last statement above, this factor does indeed play a role in the acceptability criteria because most individuals living near to a Nuclear power station are indeed bearing higher risk in proportion to their benefits. Some individuals might however be receiving more benefits if they have a job directly related to the station. According to VST, this criteria should be conservative for the Hvalfjörður Tunnel but one might wonder why particularly this criteria was used and is it really appropriate having in mind that the HSE criteria was constructed for other purposes than road safety?

In chapter 2.0 the reports author(s) decide to analyse four types of fire; fire in a small vehicle, light fire in a heavy vehicle, fire in a heavy vehicle and fire in a hazardous cargo transportation fire.

Comments:
These types of fires should indeed represent generally the scale of almost all possible fires in tunnels.

In chapter 3.0 consequences from fires are analysed. The hazard zone is defined as the driver and passenger of the burning vehicle and all those who are downstream from the burning vehicle approaching the burning vehicle until the tunnels are closed by the operator. Statistics on origin of fires, effects from extinguishers on fires and historical statistics on fire frequency is given. Fatality rate for people in the hazard zone is then given depending for the four types of fires.

Comments:
The estimation of fatality rate seems to be based on expert judgement after consideration of origin of fires, effects from extinguishers on fires and from historical statistics. These facts have unfortunately nothing to do with how fires in tunnel effect humans, only the origin and how severe they might get. Fatalities rates given must thus be taken as a some kind of mixture of many factors controlling the outcome. Other legitimate questions are also left to the reader, namely how is account for the length and shape of the tunnel taken? Shouldn't the placement of the fire matter somehow? Would another tunnel, with a different shape, traffic and length have the same fatality rates for people in the hazard zone? Is the fatality rate perhaps taking account of all these factors?

In chapter 4.0 probabilities for the respective fire types are presented. Probabilities are derived from statistics published in various PIARC publications. An account of the slope is taken by adding 30% to the probability.

Comments:
Why 30% are added and not 10% or 100% is also probably based on some PIARC publication but no specific reference is given and therefore impossible to verify that 30% can be regarded as conservative or not.

In chapter 5.0 more statistics regarding variation of traffic density is added. Account for variation in the traffic is done by splitting the traffic into four groups depending on winter or summer and night and day. Finally, results from the calculations are presented in various FN curves depending on estimated response times and future traffic. The FN curves fell in the ALARP region and the average individual risk was estimated to be $1.5*10^{-6}$.

Comments:
Having in mind that traffic varies also by days and time of day, more effort should have be taken to account for this variation. Variation on more than one variable would have been preferred as there are many more uncertainties and perhaps larger uncertainties involved.

In chapter 6.0 ways to reduce the risk are presented. Based on the calculation model, minimizing the response time is thought to be the most effective way to reduce risk as that minimizes the number of people in the hazard zone. The report states also that moving transport of dangerous goods to a low traffic periods will reduce both frequencies and consequences from such catastrophes.

Comments:
It is easy to understand that lower traffic means fewer exposed (reduced consequences) but it is hard to understand why frequencies should also reduce. Few ideas of reducing the risk are probably a consequence from using a relatively simple model.

Chapter 7.0 summarizes briefly the results and main findings. In general it is stated that the risk is high compared to global experiences of tunnel operations.

Comments:
Two interpretations from this conclusion are left to the reader, namely weather the risk presented is conservative or if the risk is indeed higher in Hvalfjörður Tunnel than global experience? This is a very important point because if the risk is higher, why should people in Iceland accept to bear higher risks than other people in other countries?

General comments:
The report in general is brief and clear on what assumptions are being made and results are interpreted clearly. There are however assumptions in the report which are hard to validate. Uncertainties in the model are also only partly analysed.

3.4.2 Assessment on risk from transport of dangerous goods by the department of Justice

Another assessment was done by a group nominated by the department of justice. That grouped made a qualitative judgement on risks inside the tunnel by looking at accidents in other tunnels and by doing quantitative calculations using a model which is currently being developed by a joint research group from Piarc and OECD. This model was and is still under development but is supposed to be released in the year 2004. In the joint Piarc and OECD model, risks were evaluated from 10 scenarios which all were due to transportation of dangerous goods. Of those 10 there were two fire scenarios, 20 and 100 MW fires which strangely resulted in maximum 1 death in the 100 MW fire and zero in the 20 MW fire. The methodology of this model is well described in a report from OECD and Piarc (1999) but numbers showing how consequences are estimated exactly are sadly not available. Results from the group nominated by the department of justice resulted in regulations were traffic of dangerous goods is prohibited at certain times, see effects in Figure 10.

3.4.3 What needs to be improved?

Summarizing the above analysis on previous risk assessments, the following points needs to be improved.

- Risk analysis reports should be as transparent as possible. All assumptions must be clearly and thoroughly documented. Doing that will increase the credibility of the analysis.
- Criterion for the acceptable level of risk needs to be considered. Are appropriate criteria being used and are other aspects that need to be considered?
- Merging many factors into a single number makes it almost impossible to measure changes in these factors. Variables like fatality rate should therefore be based on combination of as many variables as possible or reasonable. By going deeper into the problem should also give a better understanding of the object and therefore more ideas of ways to reduce the risk.

- Uncertainties should be analysed.
- A better account for variation in the traffic is preferred as it can be expected that the number of deaths from fires are strongly related to traffic.
- The placement of fires inside the tunnel should be considered.

4 RISK ANALYSIS FOR THE HVALFJÖRÐUR TUNNEL

In this chapter, risk analysis for the Hvalfjörður is performed according to the Probabilistic Analysis method. The chapter is divided into 3 sub chapters, starting with 4.1 where all possible sources of hazards are identified. These hazards are evaluated roughly in order to quickly choose which of those need further considerations. Chapter 4.2 includes estimation on frequencies for those hazards being considered. Chapter 4.3 describes finally possible scenarios including estimation of their respective frequencies and consequences. In order to estimate fatalities from fires in a tunnel a model had to be constructed. A thorough description on how this model was constructed can be found in Appendix A.

4.1 Identification of different Hazards and scope

The process of identifying hazards was mainly done by a literature study but also through talking with different people and different experts. All thinkable hazards, sorted by their nature, where found to be as follows:

a) Collisions of vehicle (without fire)
- Frontal
- Side
- Back
- Walls
- Turn over
- Objects

b) Fires
- Car
- Van
- Bus
- Heavy Goods Vehicle (HGV)

c) Accidents involving transport of dangerous goods
- Oil Tanker
- Propane gas release
- Chlorine release
- Ammonia release
- Explosion, TNT

d) Health risks
- Presence of dust Particles
- Presence of Toxic exhaust from vehicles, NOx, CO and more.

e) Natural disasters
  - Earthquakes
  - Flooding
  - Volcanic eruption

f) Social risk
  - Sabotage and terrorism

Hazards in categories a) through c) can be thought of as highly thinkable hazards with potential to be catastrophic and should therefore be further analysed.

Health risks might have immediate consequences to people that are particularly sensitive like those who have asthmatic predisposition to air pollution, but to majority of people, health risks in Hvalfjörður Tunnel are not a direct threat but in the long term they might have negative health effects, especially for people using the tunnel frequently. The ventilation system in the tunnel is also controlled by measuring CO inside the tunnel but as Piarc (2000) points out then CO emissions from vehicles have decreased substantially over the years with better engines and it is therefore doubtful that controlling the ventilation through CO is sufficient. Health risks should therefore be evaluated.

Natural disasters like earthquakes and flooding are risks that many people first though of when the tunnel was new. This is pretty rational thinking because the tunnel goes under the sea and is situated in a country where earthquakes are not regarded as rare events. However, according to a study by Sigbjörnsson, Einarsson, Erlingsson and Þráinsson (1994) then earthquakes are not regarded as a serious threat to the tunnel structure and only minimal damage is expected in the biggest earthquakes. Volcanic eruptions in the area of the tunnel are not either expected. The tunnel is also well equipped to pump out water coming in either from the tunnel portals (rain) or from minor leakage in to the tunnel. A sudden opening of huge water stream is hardly thinkable and if it could happen it should perhaps have happened during the time it was being blown out. Assuming that minor leaks are only possible, even if all pumps would fail, there would be plenty of time to close the tunnel for traffic, as there is a water reservoir in the bottom which is closely monitored by the tunnel operators. Summarizing the case of natural disaster, there is no indication that earthquakes might damage the tunnel severely or create sudden flooding. The tunnel is not situated on an active volcanic spot. Natural disasters causing danger in the tunnel are events which are regarded by experts in the field as highly unlikely and therefore no further consideration of such events is needed.

Hazards from sabotage and terrorism are thinkable but very unlikely. Effects from such are perhaps included in categories b) and c) and conclusions of the tunnels vulnerability against sabotage and terrorism can be drawn from those hazards.

Hazards in categories a) through c) will be investigated further in the following chapters but only a brief discussion will follow about the tunnels vulnerability against sabotage and terrorism. Unfortunately time did not allow a thorough investigation on health risks.

4.2 Assessment on frequency for different hazards

4.2.1 Frequency of Collisions

Based on accidents and driving data from Vegagerðin (Public road Administration of Iceland) the following frequencies of all traffic accidents could be calculated, see Table 2. It is assumed that these data include all accidents, collisions, fires and DGA. Fires and DGA are indeed very rare events so their share in the total accident frequency is very little. Frequency of collisions is thus a little lower than Table 2 indicates but account for fires and DGA is taken in chapter 4.2.4.

Table 2. Traffic Accidents in Hvalfjörður Tunnel compared to other roads.

	Total traffic work (millions of vehicle km)	Traffic accidents per million vehicles	Traffic accidents per million vehicle km	Traffic accidents with injuries per million vehicles	Traffic accidents with injuries per million vehicle km	Killed in traffic accidents per million vehichles	Killed in traffic accidents per million vehicle km on highways
Hvalfjörður road, 1993-1997	227	59.39	0.91	15.13	0.23	0.857	0.013
Hvalfjörður tunnel 1998-2001	22.1	5.81	1.01	1.59	0.23	0.000	0
Difference (Road/Tunnel)		10.22	0.91	9.55	1.00		
Rural roads in Iceland 1995-1999			1.04				
Rural Roads in Faroe Islands 1991-1999			1.02		0.40		0.014

It is interesting to notice that the total rate of traffic accidents in Hvalfjörður Tunnel is slightly higher than on the road if compared to per million driven km. Comparing this to million vehicles then the rate for the road is 10 times higher. The explanation for this difference is simply the fact that the road is roughly 10 times longer than the tunnel.

The frequency of accidents in tunnels is usually lower than on roads because driving conditions are almost all in favour of tunnels. A likely explanation for the relatively high accident rate in Hvalfjörður Tunnel are many but mainly because it is a relatively new tunnel and accident rates in tunnels are often high in the beginning but tend to get lower as drivers get familiar with the tunnel environment. Figure 11 complies with this theory as it shows the development of accident frequency since the tunnel was opened.

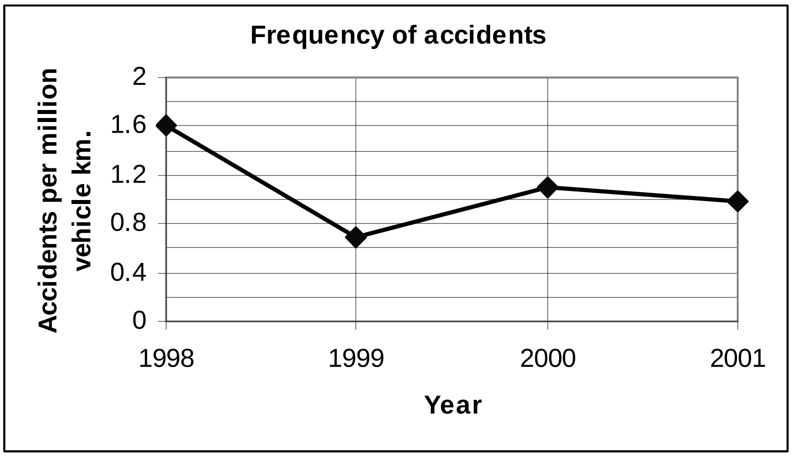


Figure 11. Frequency of accidents in Hvalfjörður Tunnel.

4.2.2 Frequency of Fires

According to PIARC (1999), fires are mainly caused by:

- Electrical defects (most frequent in light vehicles).
- Brake overheating (60% to 70% of all fires in lorries).
- Other defects.

Far less frequent causes mentioned are:

- Collisions.
- Technical defects of tunnel equipment or maintenance work.

According to Norwegian research by Amundsen, Engebretsen and Ranes (1997) some fires might also be set on purpose.

A French study, investigated fires in tunnels and classified them according to their importance, see Table 3.

Table 3. Estimations on Fire Rates in French Tunnels (Piarc,1999).

Classification of fire		Cases of fire for 10^8 veh x km
Passenger vehicle	Fires of any importance	1.5
Lorries whithout dangerous goods	Fires of any importance	8.0
	Fires with some damage to the tunnel importance, less than 20 MW	1.0
	very serious fire, larger than 20 MW	0.2
Lorries transporting dangerous goods	Fires of any importance	2.0
	Fires with involvement of the dangerous	0.3

To estimate the frequency of fires in Hvalfjörður Tunnel, all available statistics on tunnel fires were gathered. These data were obtained from Piarc (1995 and 1999) and are shown in Appendix C.

When looking at the statistics from these various sources it became apparent that the degree of variation between tunnels is huge, for example, number of fires varied from zero to 25 fires for every driven 100 million vehicle km, see Figure 12.

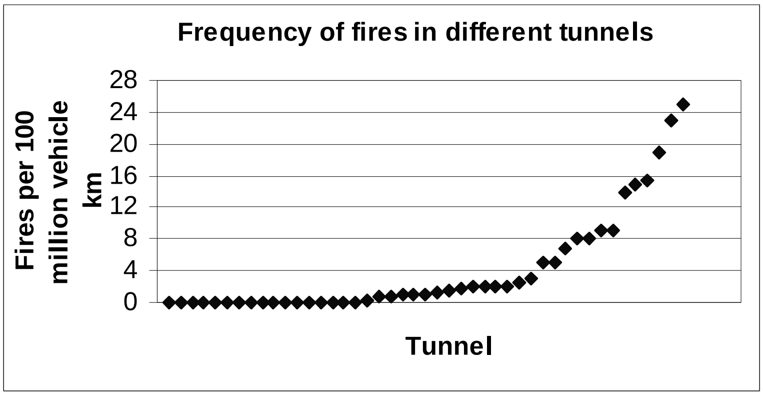


Figure 12. Frequency of fires, each dot represents a single tunnel, adapted from Piarc (1995 and 1999)

What Figure 12 also shows is that majority of tunnels seem to have a very low frequency and many, no fires at all. The average rate was 4.1 with a standard deviation of 6.5 fires per 100 million vehicle km while weighted average proved to be a little higher or 4.7 fires. A deeper look into the statistics revealed however that many of these tunnels give frequencies based on very little traffic volume, even less than 1 million vehicle km. Tunnel fires are very rare events so one fire in a tunnel can enhance the statistics greatly. Other factors explaining this difference is the fact that tunnels are indeed different in shape, length, slope and more which plays a role in the probability of a fire event. Steeper slopes are for example known to increase the rate of fire because the rate of a motor breakdown and overheating of brakes will increase. The report system differs also between tunnels and countries. Tunnels that have sophisticated TV-surveillance systems and 24 hour manned control room are more likely to report all fires than tunnels that have little or no surveillance at all. There is also another aspect, namely how people define a tunnel fire? Someone might classify a motor breakdown with a smoke production as a tunnel fire while others might not!

In an attempt to narrow this band of different frequencies it was decided to include only information from tunnels which had a history of more than 100 million vehicle km and only those who are bidirectional. After exclusion of those tunnels that didn’t match, 11 tunnels were left, see Table 4 and Figure 13.

Table 4. Tunnels which all are rural, bidirectional and include more than 100 million vehicle km (Piarc 1995, 1999)

Country	Tunnel	Length [km]	Years inquired	Average Annual traffic [million veh/year]	Total Traffic Work in million vehicles km	ALL vehicles	Heavy vehicles
						Rate per 100 million vehicles km	Rate per 100 million vehicles km
Austria	Arlberg*	14	1987-1991	1.7	119	2.5	-
Austria	Katschberg*	5.4	1987-1991	3.9	105.3	0.0	0
Austria	Tauern*	6.4	1987-1991	4.5	144	0.0	0
Switzerland	Seelisberg*	9.3	1981-87	4.2	273.42	2.0	-
Switzerland	Belchen*	3.2	1978-86	11	316.8	1.0	-
Switzerland	San Bernadino*	6.6	1968-87	1.7	224.4	5.0	-
Switzerland	Gothard*	16.9	1981-87	3.7	437.71	3.0	-
France	Epine	3.1	1984-91	8.4	208.32	1.1	40
France	Mont Blanc*	11.6	1965-92	1.1	357.28	5.0	
France	Chamoise	3.3	1988-1992	8.5	140.25	6.8	22.6
France	Fréjus*	12.9	1981-91	0.9	127.71	9.0	

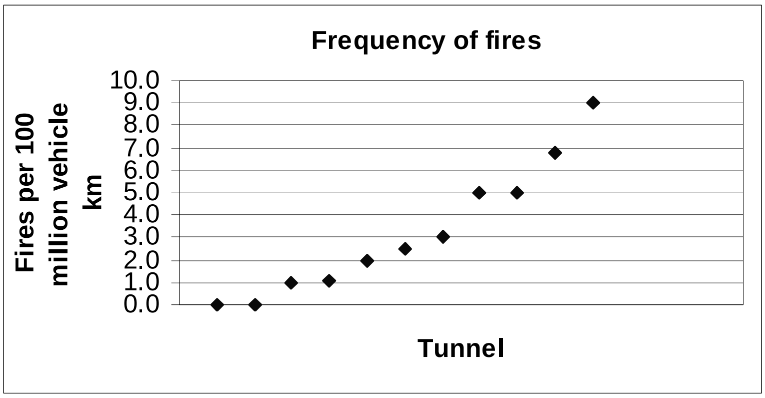


Figure 13. Frequency of fires in 11 tunnels (Piarc 1995, 1999).

The average frequency for these tunnels was found to be 3.14 with a standard deviation of 2.9 per 100 million vehicle km.

Which frequency is now to be expected in Hvalfjörður Tunnel? Is it possible to draw any exact conclusions from above statistic? Is one fire more likely than nine? To answer this it was decided to use Bayesian updating (see 2.2.3.2). The a priori distribution was estimated as a uniform distribution where 0.5 fires per 100 million vehicle km is as likely as 9. With new information regarding total traffic and number of fires the posteori distribution could be calculated, namely that one fire had occurred from the time of opening till 1 of august 2003 (29,931,011 vehicle km). The a priori and posteori distributions can be seen in Figure 14.

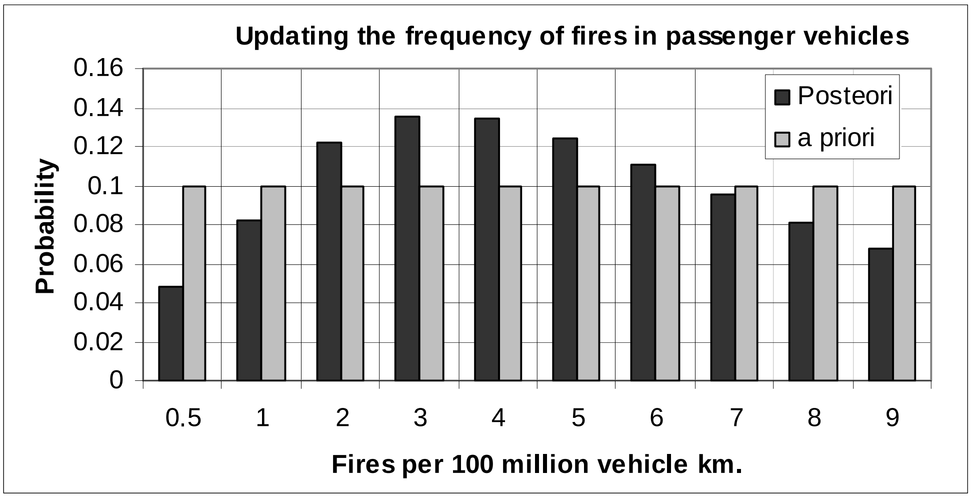


Figure 14. Bayesian approach for the Fire Rate in Passenger Vehicle

As Figure 14 shows then it's most likely that the fire rate is somewhere between 2 and 5 fires per 100 million vehicle km. The average fire rate for the a priori distribution was 4.55 which lowered to 4.50 in the Posteori distribution.

Because information about the heavy vehicle fires were so limited (see Table 4), it was decided to use the value given by PIARC (1999) in Table 3 or namely 9.2 fires per 100 million vehicle km. A Poisson density distribution was thought as an appropriate distribution for this value, see distribution in Figure 15.

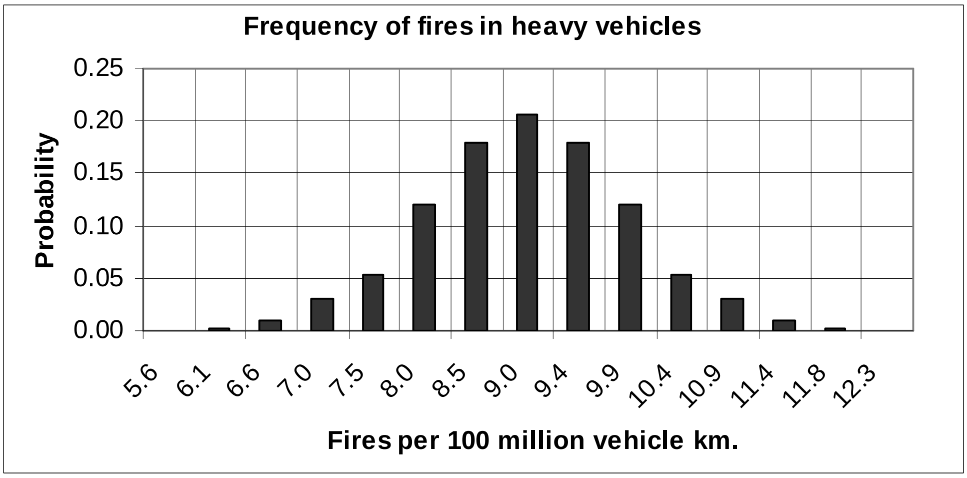


Figure 15. Density distribution for the fire rate in Heavy Vehicles

4.2.3 Frequency of Dangerous Goods Accidents

To estimate the frequency of dangerous goods accidents, a model called the VTI-model was used (Räddningsverket, 1996). This model was developed in Sweden by the Swedish Rescue Service Agency (Räddningsverket) and gives estimation for the frequency for a dangerous goods accident where the substance leaks out. A detailed calculation procedure is found in appendix E. Consequences for DGA where not calculated according to VTI. Results from an uncertainty analysis indicated that the base frequency follows a normal density distribution where the average is 19.9 accidents per 100 million DGA vehicle km with a standard deviation equal to 3.3, see Figure 16.

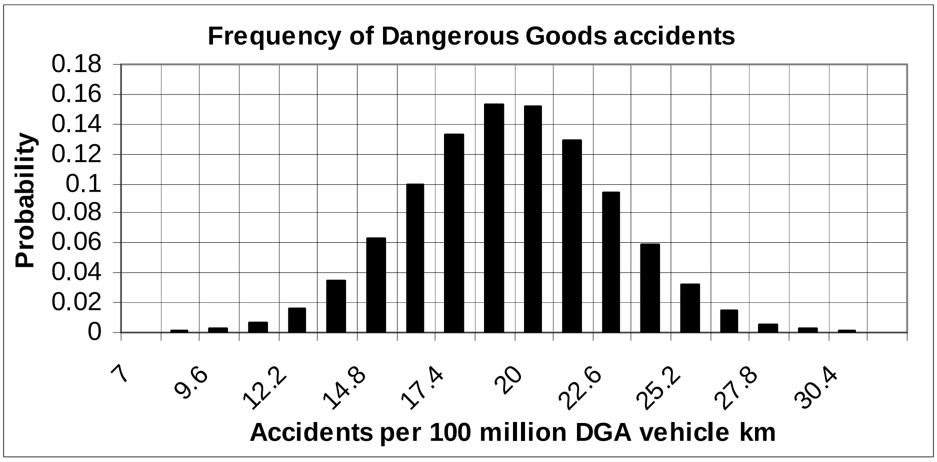


Figure 16. Rate of dangerous goods accidents

Comparing this to experience in Iceland, according to Guðjónsson (2000), 1 accident involving leak of petrol during a history of 8.050.000 vehicle km (1996-2000) had occurred. In the year of 2003 another accident involving petrol transport vehicle transporting turpentine (Morgunblaðið, 2003). The third accident occurred inside the Hvalfjörður Tunnel where a petroleum tanker leaked few tenths of kilos of petroleum. Assuming that equally amount of driven km per year the frequency could be estimated to be around 21 accidents per 100 million vehicle km. This number is very similar to results from the VTI model. In the first two accidents the cause was a slippery road and in the other a road edge which collapsed. In the third accident petroleum was thought to have leaked through an air pipe due to an overfilled tank. Fire did not start in any of those accidents.

4.2.4 Summary of Accident Frequencies

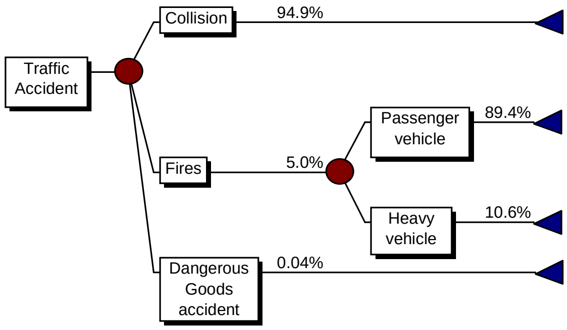
A summary of all base frequencies are given in the following table.

Table 5. Summary of accident frequencies.

	All	Passenger Vehicle Fire	Heavy Vehicle Fire	Dangerous Goods Accident	Collisions
Accident rate per million vehicle km	1.008	0.0453	0.092	0.199	0.960
Yearly frequency	7.23	0.324	0.038	0.00302	6.86
Average return period (years)	0.138	3.09	26.1	331	0.146
Probability of an outcome given an accident has occurred	100%	4.48%	0.529%	0.0418%	94.9%
Frequency of all vehicle fire per year	0.36				
Average return period for vehicle fire (years)	2.8				

The sum of all accidents was calculated by multiplying each category with it's respective fraction of total traffic. Note that collisions are expected to be 95% of all traffic accidents.

An event tree based on this classification was constructed; in order to be able to calculate frequencies for different scenarios arriving from these base events, see Figure 17.



Base Scenario	Yearly frequency	Return period (years)	Frequency per 100 million vehicle km
A	6.86	0.146	90.5
B	0.324	3.09	4.27
C	0.0383	26.1	0.505
D	0.00302	331	0.0399

Figure 17. Event tree for traffic accidents in Hvalfjörður Tunnel

Note that these events represent only the base scenario, which can lead to many different sub scenarios, depending on circumstances. Fire in a passenger vehicle might for example be extinguished quickly causing little harm while another might evolve into a catastrophic fire. Sub scenarios for each base scenario (A-D) will thus be produced in the next chapters.

4.3 Assessment on consequences

For each collision, vehicle fire or dangerous goods accident there are numerous possible scenarios. For each hazard, different event trees were constructed and frequencies calculated. Scenarios were chosen to represent the widest range of possible scenarios.

Vehicle fires were split up in two different classes, that is a fire in passenger vehicles and a fire in a heavy vehicle. In order to calculate consequences from fires in the tunnel a model had to be built. A detailed description on this model is found in Appendix A. In order to predict velocity of wind during different sizes of fires a CFD (Computational Fluid Dynamic) model had to be built. The CFD calculations were done using a program called FDS (Fire Dynamics Simulator) from NIST (National Institute of Standards and Technology). A detailed description of this is found in Appendix F.

4.3.1 Collisions

Possible scenarios from collisions inside the tunnels as pointed out earlier are:

- Frontal
- Side
- Back
- Turn over
- Tunnel walls
- Objects

Sources to quantify probabilities for the above scenarios were unfortunately not found. It was therefore decided to estimate only the expected fatality rate in the tunnel due to collisions. Data to assess this rate were obtained from Vegagerðin (Public Road Administration). FN – curves for collisions could not be constructed because the data wasn’t sufficient.

During a 5 year period on Hvalfjörður Road there were 3 fatal accidents while there hasn’t been a single fatal accident in the tunnel. In all those 3 fatal accidents, a vehicle glided off the road. It is however not possible to state that the frequency per driven km is lower in the tunnel as there have been only driven 30 million vehicle km (during the period: 11.07.1998 - 1.08.2003) and the frequency for fatal accident in the road was one per 75.6 million vehicle km. Comparison of actual accident frequency in rural roads and in Hvalfjörður Tunnel shows that the accident frequency is very similar in both. To get some rough idea about general driving conditions in the tunnel and on the road, the following can be stated (note that this not a thorough list):

Condition inside Hvalfjörður Tunnel:

- Visibility is similar throughout the year.
- The road is always dry, hence never slippery.
- No cross winds inside the tunnel.
- Maximum speed is 70 km/h
- Constant speed control (speed cameras located inside).

- When driving in or out of the tunnel, drivers have to adjust to different light
- Driving offside in the tunnel is obviously not possible (fatal singular accidents unlikely)

Conditions on Hvalfjörður road:

- Visibility is changing according to daylight and weather conditions (fog, snow etc.)
- The road can get icy at winters
- Crosswinds are common.
- Maximum speed is 90 km/h
- Limited speed control.
- No light adjustment.
- Driving off the road is possible (fatal singular accident thus likely)

All points except the one about the light adjustment at the tunnel portal are in favour of the tunnel.

In Hvalfjörður road, all fatal accidents where singular, that is the vehicle glided off the road. It seems therefore reasonable to estimate that the frequency of a fatal traffic accident in Hvalfjörður Tunnel is going to be lower than generally in rural roads. More data is however needed to draw any exact conclusions about the frequency of fatal accidents. Assuming that fatal accidents are directly in proportion to all accidents, the frequency of fatal accidents should be the same as rural frequency because accident frequencies are identical. Fatal accidents rate in Hvalfjörður Tunnel can thus be estimated to be as high as 1.3 fatal accidents per 100 million vehicle km., see Table 2, or 0.099 fatal accidents per year which means that average return time for deadly collision is about 10 years. This estimation is associated with some degree of uncertainty but should be conservative having in mind that driving conditions are mostly in favour of the tunnel. Note that this number denotes the average number of fatalities in the traffic due to collisions. In a single collision there might more than one fatality but statistics that show the frequency for more than one person being killed in the traffic were unfortunately not obtainable. In the Monte Carlo simulations the frequency for single person being killed in the traffic was varied by assuming that it follows a Poisson density distribution.

4.3.2 Passenger vehicle fire

According to experience from French tunnels, about 40% of all passenger vehicle fires are extinguished quickly by nearby drivers (Piarc, 1999) and pose therefore no special threat to structure or peoples lives. The remainder of fires either burn out or are put out by a fire brigade. A fire in two or three vehicles at the same time would have to be due to a fire after collision of two vehicles where the fire spreads to the adjacent vehicle. This phenomenon is very rare and according to Piarc (1995) only two cases of such are known:

- In Germany, in the Elb tunnel, 1 fire out of 63 fires after 16 years of operation (1,6 %)
- In Italy in the Serra Ripoli Tunnel.

Another source for this phenomenon was however found in a Norwegian study (Amundsen, Engebretsen and Ranes, 1997) which covered 10 years of experience from all Norwegian tunnels. According to that study 6 fires out of 67 (9%) were reported to have started as a direct consequence from a vehicle collision. Only in one of those cases did both vehicles burn simultaneously or in 1.5 % of all fires. According to this then the probability for a two or three vehicle fire might be estimated to be in the order of 1-2 %.

For a single vehicle fires, many tests have been carried out which have resulted in very different results. Ingason (2004) has gathered different tests results and the maximum heat release rate, Q_{max}, varied in those tests from 1.5-6 MW. Ingason proposed an average value of 4 MW and Foster (as cited by Ingason, 2004) proposed 3 MW as a design value for the Sydney Harbour tunnel. To account for uncertainty a triangular density distribution for Q_{max} was applied, {minimum, most likely, maximum} = {1.5,3.5,6}. All fires had a very similar growth rate of about 0.012 kW/s^2 so no account for uncertainty was needed in this case. According to Piarc (1999, 55), the total calorific value for single passenger vehicles is estimated to be approximately 6 GJ. To account for uncertainty a triangular density distribution was applied by adding and subtracting 20% to the proposed value, or {5.0, 6.0, 7.2}. From the total calorific value the duration of all fires could be calculated (t_2).
The minimum, most likely and maximum fire curve for a single vehicle fire was found to be like Figure 18 shows. Fire curves used in the uncertainty analysis lie between the minimum and maximum curve.

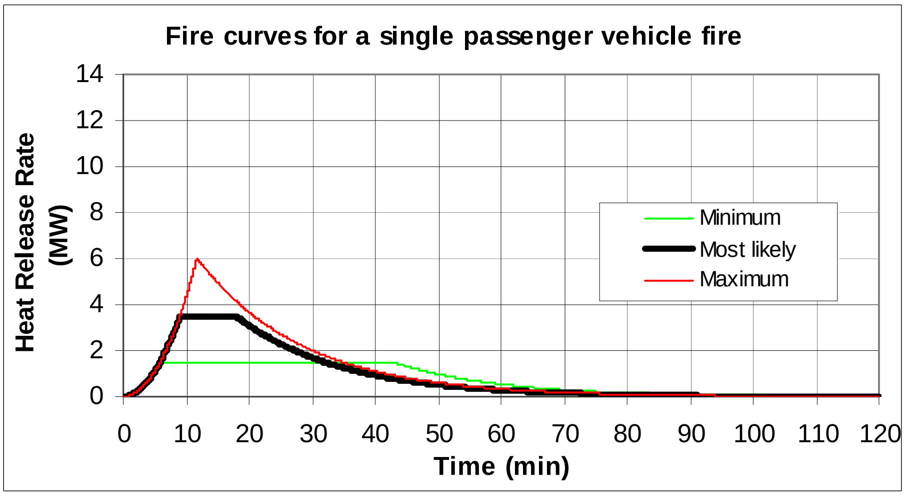


Figure 18. Fire curves for a single passenger vehicle fire.

For the two to three vehicle fire, Piarc (1999,63) proposes a 8 MW maximum heat release rate. Account for uncertainty here was estimated by using available information from the single passenger vehicle fire. Q_{max} was estimated to have a triangular density distribution {4, 8, 12} and the energy content was estimated by multiplying with 2.5 or {12.5, 15, 18).

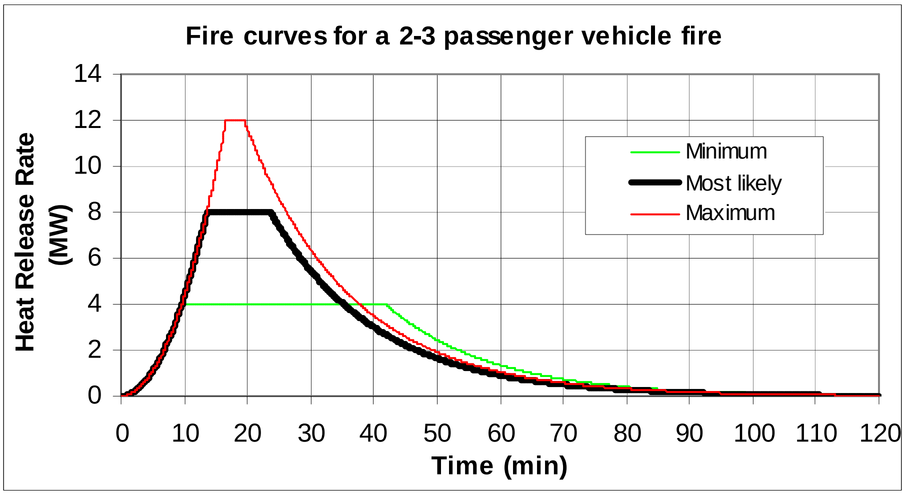
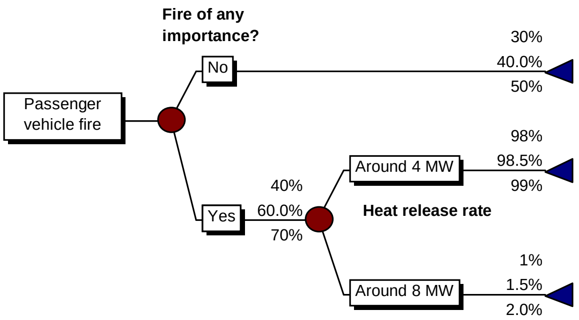


Figure 19. Fire curves for 2-3 passenger vehicle fire.

From Figure 18 and Figure 19 it can be concluded that fire brigades are not going to have a drastic influence on the total heat release as they are expected to arrive when most of the vehicles are already burned up (assuming that they will arrive after 20-30 minutes).

Event tree for a passenger vehicle fire was now constructed with all available information in mind, see Figure 20 and frequencies multiplied with respective base frequency from Figure 17.



Scenario	Yearly Frequency in the tunnel	Average return period (years)	Frequency per 100 million vehicle km
B1	0.130	7.71	1.71
B2	0.192	5.22	2.53
B3	0.00292	342.9	0.038

Figure 20. Event Tree for a Passenger Vehicle Fire. Values above and under each probability node denote the assigned uniform density distributions values.

By calculating the wind velocity for different placements in the tunnel by using equation 6, in Appendix A, the expected wind velocity in the northern slope could, roughly, be expected to be between 0,8 to 1,0 with an average of 0,9 m/s. Calculation with FDS indicated a wind speed of 0,6 m/s. Because the wind is normally blowing from north to south in the tunnel with a velocity of 1 to 2,0 m/s then it assumed that fire will not have any affect on the velocity if the fire is in the south slope. To account for uncertainty in this parameter, a triangular density distribution was applied in the northern slope, {minimum, most likely, maximum} = {0.6,0.9,1.0} and in same way in the southern slope, {1.0,1.5,2.0}. In the same manner, the wind velocity was estimated for the 2-3 passenger vehicles fire; {0.8,1.0,1.4} for the northern slope and {1.0,1.5,2.0} for the southern slope.

Table 15 in Appendix A.4 gives information about some of the materials that are likely to be found in vehicles; unfortunately they do not give what proportion of each material is to be expected. Materials used in vehicles are also different from vehicle to vehicle and luggage can vary a lot. This is however perhaps not so important because production of toxicants are mostly dependent on how well ventilated the fire is and not on the type of material burning. For both scenarios a passenger vehicle fire in the tunnel could be estimated to be well ventilated, see calculation on oxygen content downstream from the fire in Figure 21 and Figure 23. It seemed therefore reasonable, or at least a best estimation until better information can be found, to use the average of the values given in Table 15, Appendix A, for various yields production and heat of combustion.

The reaction time was estimated to be uniformly distributed, ranging from 30-70 seconds.

A person walking out of the tunnel starting 10 meters away from the fire origin is expected to be exposed to the environment like Figure 21 shows.

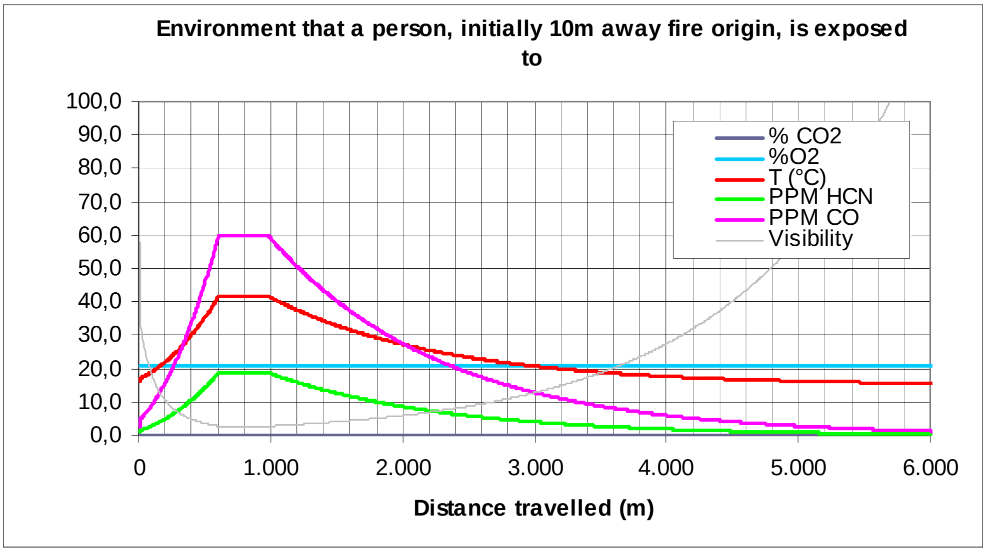


Figure 21. Exposure environment for single vehicle fire (average values used).

From this exposure the corresponding fractional effective dose can be calculated, see Figure 22.

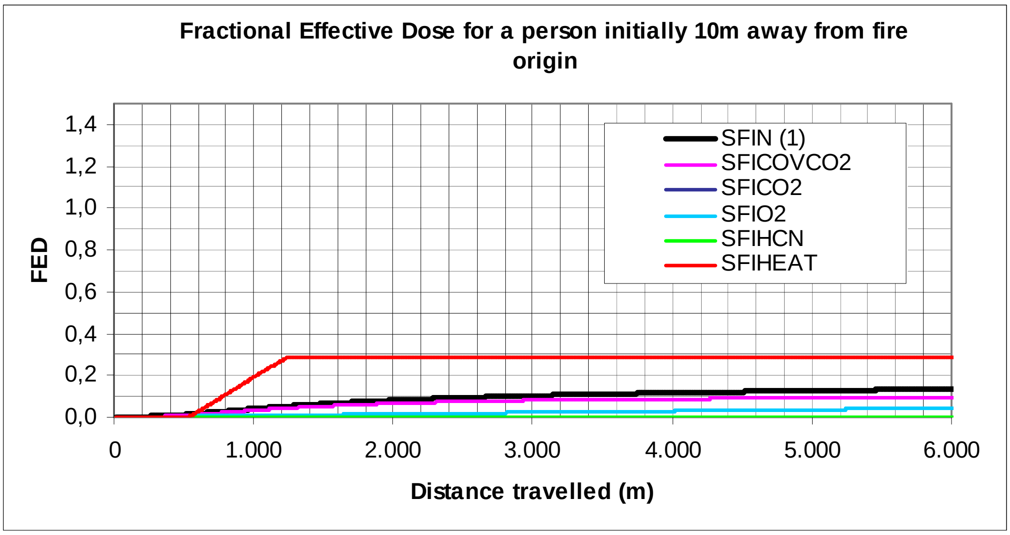


Figure 22. Fractional effective dose for single vehicle (average values used).

Figure 21 and Figure 22 show what effects the fire will have on persons exposed to this environment. When account for uncertainties was taken by doing 10,000 Monte Carlo simulations all iterations resulted in zero fatalities.

In the 2 to 3 passenger vehicle fire, the average effects were found to be like Figure 23.

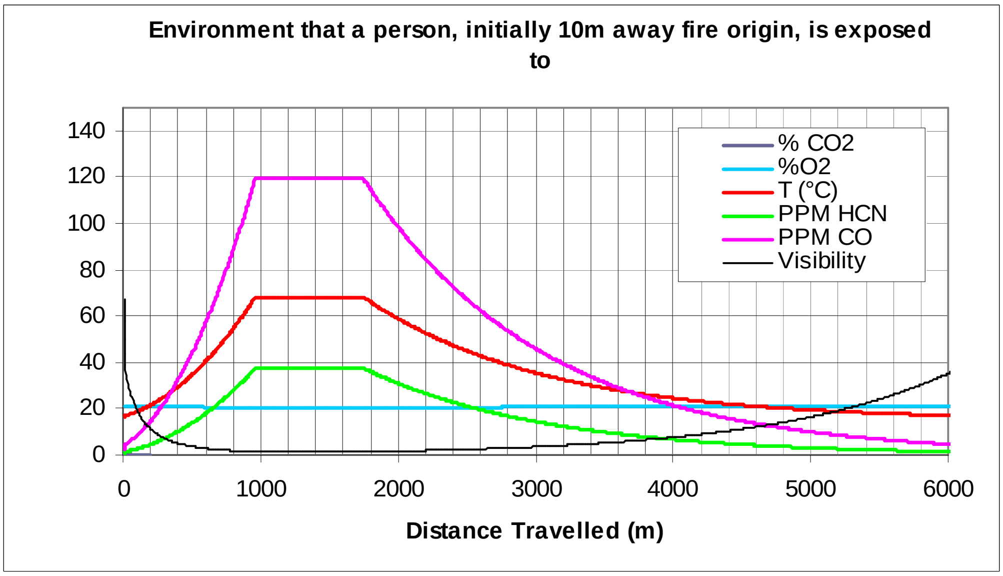


Figure 23. Effects on human for a 2-3 vehicle burn (average value used)

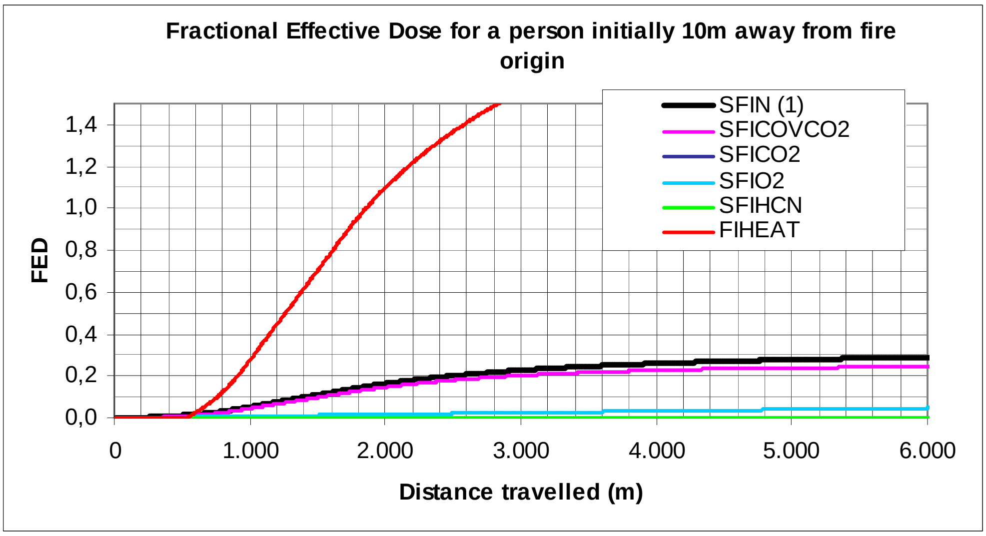


Figure 24. Fractional effective dose for 2-3 vehicles (average values used).

As can be seen from Figure 24, a person that is initially 10 meters away from the fire origin will manage to walk about 1800 m before the person incapacitates (FED=1.0) and in this analysis that point was assumed to be lethal. Results from the Monte Carlo simulations for this scenario are summarized below but also in Table 7.

Minimum fatality: 0 persons
Maximum fatality: 106 persons
Average: 4.9 persons
Median: 0
Standard deviation: 10.6 persons
95 percentile: {0;33.4}
90 percentile: {0;18.4}
66.9% of all iterations resulted in zero fatalities.

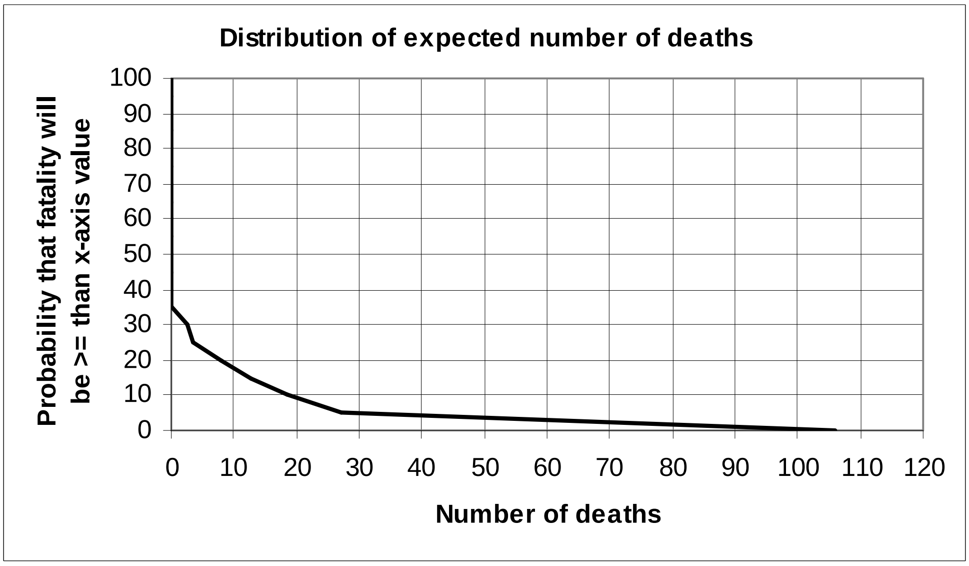


Figure 25. Distribution of all iterations in the Monte Carlo simulation.

Figure 25 shows the possibility of outcomes, using the Monte Carlo simulation. This figure shows clearly the uncertainties involved. If one had chosen average values for all variables then that would have resulted in zero fatalities but if all variables would have been chosen to maximize the number of deaths, that would have resulted in 106 fatalities.

4.3.3 Heavy Vehicle Fire

By using estimations on fire frequencies in Table 3 it can be concluded that fires of any importance are 87% of all fires and 11% are less then 20 MW, causing some damage to the tunnel and very serious fires are 2%. From this information it can be concluded that 87% of all lorry fires caused no fatalities and are therefore not of any importance! Given this information, it was decided to look at three sizes of fires, namely a small heavy vehicle fire, a bus fire and a large heavy vehicle fire.

PIARC, French and NFPA standards indicate that the maximum heat release rate in a bus fire is approximately 20 MW while some tests indicate 29-34 MW (as cited by Ingason, 2001). Ingason (2004) proposes 30 MW. A triangular density distribution was therefore applied where the minimum value of Q_{max} was set to 20 MW, most likely to 30 MW and the maximum to 34 MW. The growth rate for a bus fire is estimated by Ingason (2004) to be approximately 0.1 kW/s^2 or close to the ultra fast fire curve according to NFPA. No information was found regarding upper and lower limit on the growth rate and and therefore to account for uncertainty in this variable a +/- 20% uncertainty was applied to the growth rate and a triangular density distribution applied on those values, that is {0.08, 0.1, 0.12}. The total calorific value for a public bus can be estimated, according Piarc (1999) to be about 41GJ and according to Ingason (2004) about 54GJ. A uniform density distribution was therefore applied to the energy content with a minimum value of 41GJ and a maximum of 54GJ. It is assumed that the fire will not spread to adjacent vehicles and it is further assumed that the fire brigade won't have any significant effect on the fire, that is the bus will burn out. The fire curves for the bus fire were calculated to look like Figure 26 shows.

Figure 26. Fire curve for a bus fire.

By using equation 6 and results from the FDS calculations the velocity of wind in the northern slope was estimated to be between 1.6 m/s and 2.0 m/s with an average value of 1.8 m/s. In the southern slope the wind was estimated to be between 1.4 and 2.0 m/s with an average value of 1.6 m/s. To account for uncertainty in this parameter, a triangular density distribution was applied in the northern slope, {minimum, most likely, maximum} = {1.6, 1.8, 2.0} and in same way in the southern slope, {1.4, 1.6, 2.0}.

This fire is also expected to be well ventilated and therefore same values for various yields production and heat of combustion was used as in the passenger vehicle fire case.

It is very difficult to assign a single fire curve to heavy goods vehicle fires as the type and magnitude of fire load varies greatly. Table 14 in Appendix A recommends 15-130 MW fire while Piarc (1999) is expecting the general lorry fire to be about 20-30 MW. The latest results in this field come from a full scale tests in the Runehamar tunnel in Norway, which were performed in September 2003. They indicate that there might be potential for even higher heat release rate or over 200 MW (Ingason, 17 October, 2003).

It was decided to look at two cases of fires, a 15 MW fire and a 130 MW fire as the range of possible fires is so great (over factor 10). The latter fire represents thus in fact a catastrophic fire. In both cases it was assumed that the time to reach peak HRR would be approximately 13 minutes (α_{15MW} = 0.025 and α_{130MW} = 0.215). The total calorific value in the smaller fire was estimated according to Piarc (1999) to be about 65 GJ which corresponds to 2212 kg densely packed wooden pallets, 310kg plastic mixed with pallets and 332 kg of rubber tires. According to Piarc (1999), then calorific value in the second might typically be about 87 GJ which corresponds to a 2000 kg of upholstered furniture. To account for uncertainty in above numbers it was decided to vary them in the Monte Carlo simulation by +/- 20%. If no account is taken for the possibility that the fire might spread to adjacent vehicles then the fire curves for these two case look like Figure 27 shows.

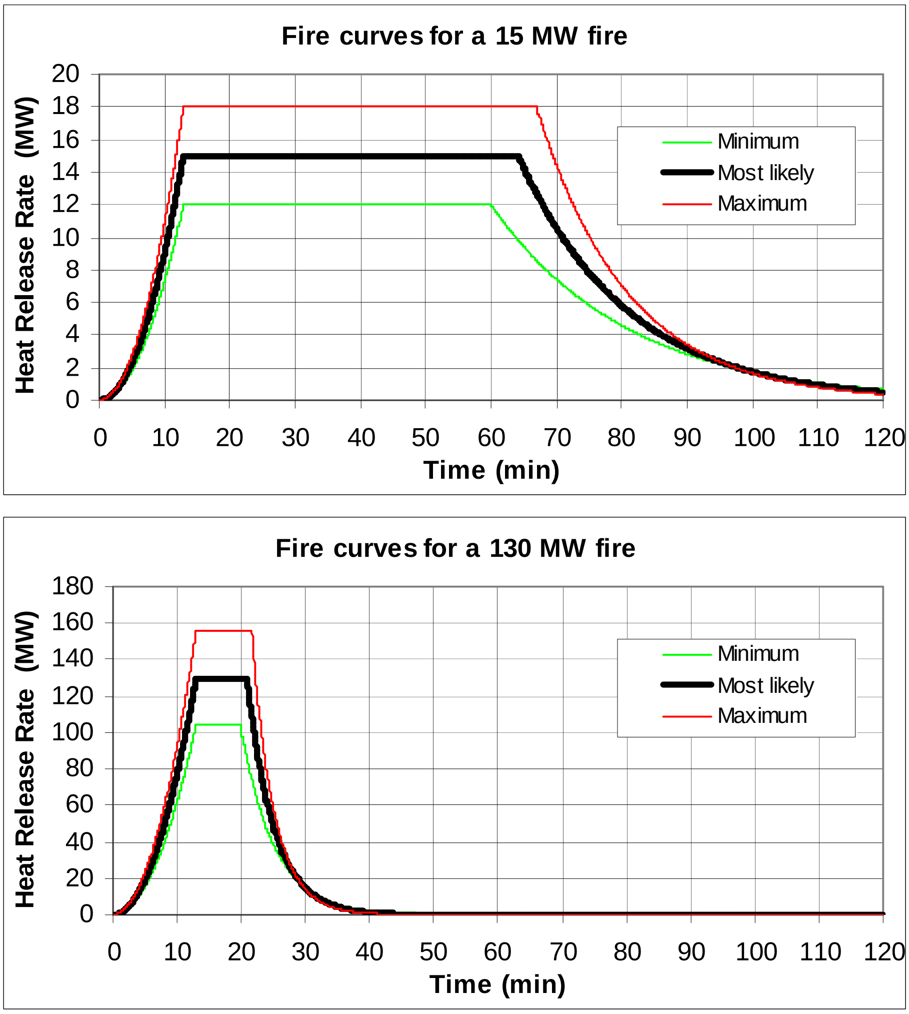


Figure 27. Fire curve for a Heavy good vehicle fire.

If the fire starts in the southern slope then the fire is not expected to have an effect on the wind velocity, thus a triangular density distribution describing the normal wind was used, that is {1.0,1.5,2.0} m/s. If however the fire starts in the northern slope then the wind velocity is expected to be in the range 1.2 - 2.0 m/s with the most likely value around 1.7 m/s, thus a triangular distribution was applied {1.2,1.7,2} to account for uncertainty.

For HGV2 (130 MW), the wind velocity towards south is expected to be in the range 2.0 - 3.2 m/s with the most likely value at 2.9 m/s. The wind speed towards north is expected to be in the range 2.5 - 4.5 m/s with the most likely value at 3.4 m/s. These were also assigned triangular density distribution as above.

A well ventilated fire is expected in both cases and therefore the same values for various yields production and heat of combustion were used as in the passenger vehicle fire case.

An event tree showing possible scenarios evolving from the base event in Figure 17 is shown in Figure 28.

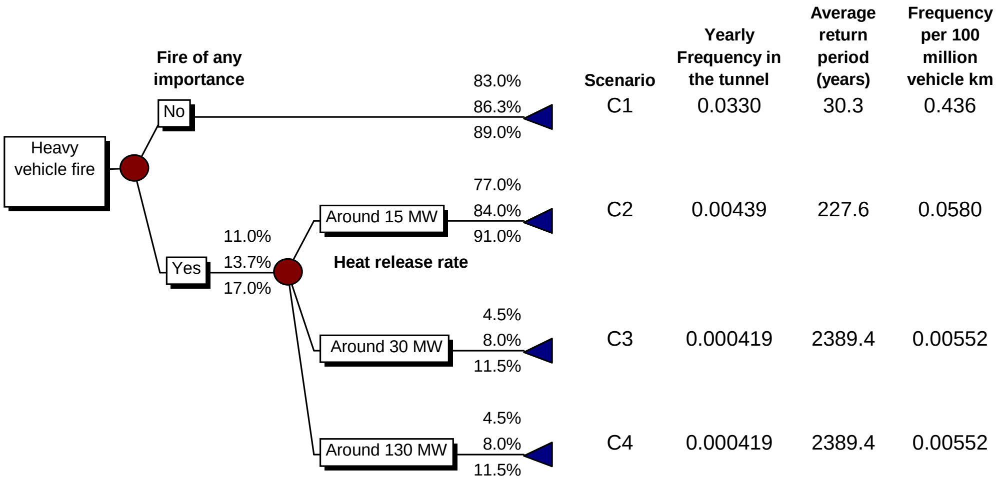


Figure 28. Event tree for the Heavy vehicle fire. Values above and under each probability node denote the assigned uniform density distributions values.

Results from the Monte Carlo simulations are summarized in Table 7 in chapter 4.3.8.

4.3.4 Petroleum Tanker

In history, only a few accidents with a petroleum tanker in a tunnel leading to a fire have happened. Probably the best known is the accident in Caldecott where a Petroleum trailer collided and overturned. An analysis of that accident showed that about 33 300 litre of petrol were burned up within 40 minutes with an estimated heat output of less than 300 MW (Satoh and Miayazaki,1989), (as cited by Ingason, 1994). A hypothesis is that after awhile, the aluminium tank melted at the top so the fire evolved from an initial spill fire into a bulk tank fire (Ingason, 1994).

When considering possible scenarios, evolving from an accident involving a petroleum tanker, there are a number of parameters that need to be considered:

- The size of the hole in the tanker and the amount of petrol in the tank, hence the flow of petrol out of the tank.
- The roadway slope.
- Existence of drainage points in the road.
- Obstacle that might effect how the petrol will spread out.
- Depth of the petroleum pool, hence the burning rate.
- Type of material that the tanker is made of. Aluminium tankers are known to soften and melt at dry parts causing the tank to open up while steel tanks can withstand higher temperatures and can generally expected to be intact, except of course were the initial hole was created
- The size of the initial spill (fire), will it lead to a bulk fire or not?
- Theoretically maximum heat release rate.

Assuming that all oxygen in a tunnel, with a 50 m^2 cross section and a wind blowing at 5 m/s, were to be used to create energy then according to Opstad (2003) as high as 900 MW of heat can be produced.

Ingason (1994) studied possible scenarios involving a petrol tanker accident, taking into account various factors and found out that the rate of heat release might range from 10-300 MW, which can be applied on Hvalfjörður Tunnel. According to Ingson (1994) a spill fire can evolve into a open bulk tank fire if the tank is made of aluminium.

It can be assumed that almost all (if not all) petroleum tankers in Iceland are made of aluminium due to the simple fact that tanks made of aluminium are much lighter than steel tankers, which results in lower transport cost. Scenarios from a petroleum tanker fire might be ranging from 10-300 MW with always the possibility of a bulk fire. It can further be assumed that a small hole is more likely then a large hole and the larger the hole, the more likely an ignition is to occur. It was therefore decided to construct an event tree for the petroleum fire based on the size of the initial hole in the tanker, see Figure 29. It was further assumed that each fire would last for approximately 1 hour. As there is so little information available regarding probabilities for different sub scenarios, probabilities were estimated using the authors own expert judgement. To account for uncertainty, values were assigned minimum and maximum values with a uniform density distribution. Percent values shown above and under each probability value in the figure correspond to this.

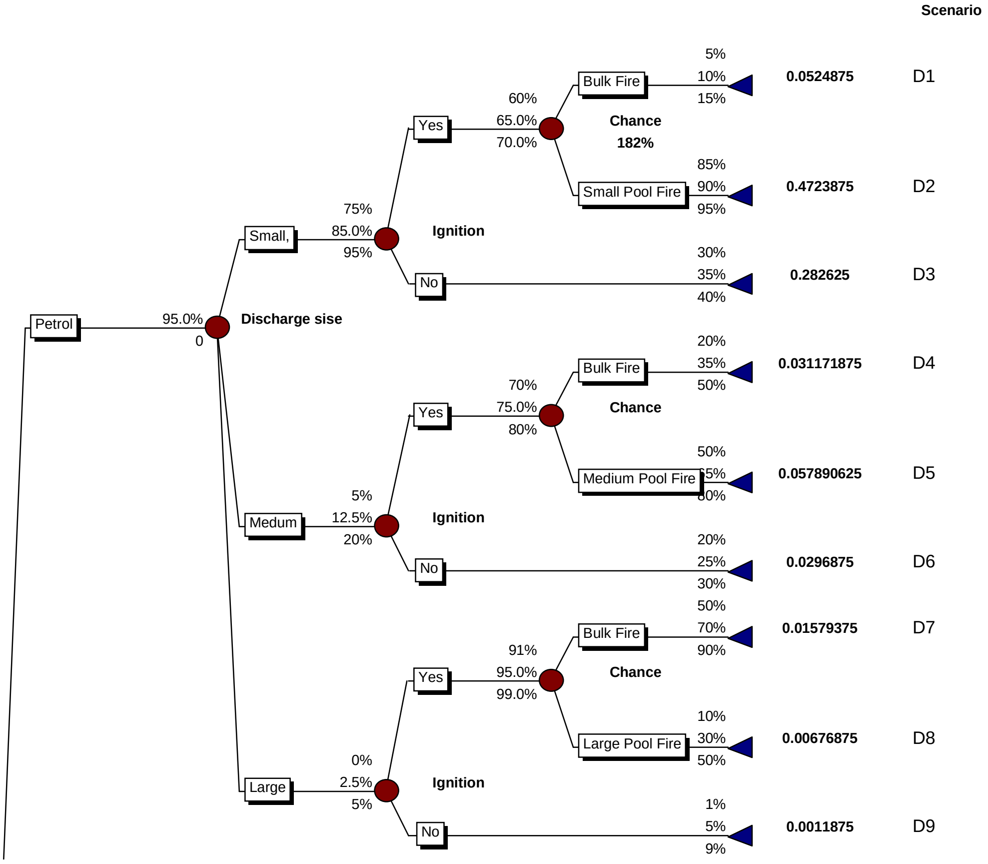


Figure 29. Event tree for a Petrol Tanker Fire.

The rate of heat release and growth rate for each scenario was estimated according to Table 6:

Table 6. Rate of Heat Release in a Petrol Tank Fire

Size of initial hole	Maximum heat release rate (MW)	Growth rate, a (kW/s^2)
Small hole,ϕ = 10-25 mm	10-50	0.19-0.38
Medium hole, ϕ = 30-50	60-200	0.38-0.76
Large hole, ϕ = 60-75 mm	200-300	1-2
Bulk Fire	200-300	1-2

Corresponding wind velocity was estimated using equation 6. Fire curves for the Petrol tank fire are shown in Figure 29.

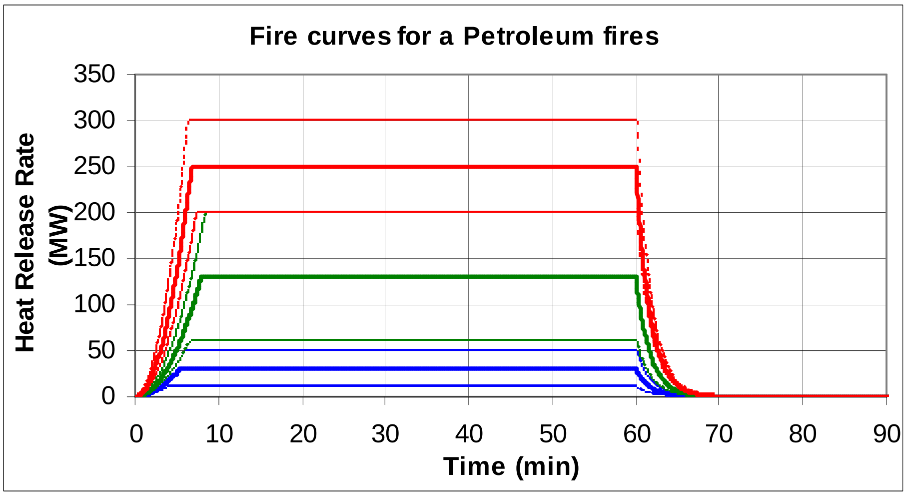


Figure 30. Fire Curves for a petroleum fires. 10-300 MW.

A large fire creates more buoyancy force in the hot smoke layer leading to higher wind velocity. The fire is thus expected to be well ventilated. This is however probably not true for the first minutes of the fire because it will take some time for the buoyancy forces to reach equilibrium. Values for different yields and for heat of combustion for gasoline were therefore taken directly from handbooks.

Consequences from a Petrol Tank fire were calculated using the same model as was used for the fire models. Results from the Monte Carlo simulations are summarized in Table 7 in Chapter 4.3.8.

4.3.5 Explosion, TNT

According to Icelandic regulations, no. 984/2000 and 684/1999, transportation of more than 50 kg of explosives is strictly forbidden in the same vehicle. Vehicles are also supposed to be clearly marked and storage of TNT should also be in a special container. There are no indications, to the author at least; that these rules aren’t obeyed thus it seems not reasonable to consider effects from more then 50 kg TNT explosion.

Based on calculation procedures as described in Merx (1992), (as cited by Persson, 2002) it was possible to calculate both the peak pressure from a TNT explosion as a function of distance from the explosion site and the expected fatality rate. According to this method, there seems to be a threshold limit of about 100 kPa peak pressure which will result in almost 100% fatality. Other sources, that Persson (2002) gathered, present a 50% fatality when a peak pressure ranges from 260-690 kPa.

A 50 kg TNT explosion in Hvalfjörður Tunnel will thus, using procedures described in Merx (1992), (as cited by Persson, 2002), result in almost 100% fatality within 29 meters (100 kPa peak pressure) from the explosion site. A person that is a little farther away, about 35 meters, will on the other hand be exposed to about 75 kPa peak pressure and will thus be safe. These calculations are approximate and they only consider the effects from a pressure wave resulting in skull-based fracture and not on secondary effects where fragments and debris hit humans. But having in mind that other sources indicate that humans can withstand up to 690 kPa peak pressure then it can be concluded safely that these results are conservative. The tunnel structure might however suffer some damage but hardly enough to cause any catastrophic damage as the tunnel itself was constructed through blowing TNT.

TNT is relatively safe to transport as it can withstand a lot of friction and shock without blowing. A fire might however set off an explosion but in most cases it will burn without an explosion. From this information it can be stated that the only possible way for an accidental explosion in a transport vehicle carrying TNT is fire and it can also be stated that minutes will pass before an explosion occurs because of the time it will take for the fire to spread and reach to the explosives. At that time when the explosion sets off it is very likely that people have evacuated farther than 29 meters away because it can be expected that they will quickly become aware of the explosion risk due to markings on the vehicle and/or warnings from the driver. Only people, perhaps trapped in their vehicle, might be in danger.

From this quantitative and qualitative judgement it can be concluded that an accidental TNT explosion is highly unlikely and the resulting consequences are expected to be minimal, only few people might be in danger. An event tree for TNT was constructed as follows and a density distribution estimated as Figure 32 shows.

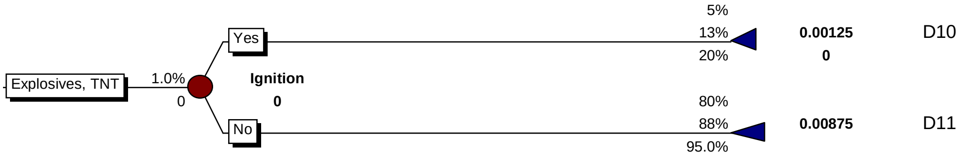


Figure 31. Event tree for a TNT explosion.

Fatalaties	P (%)
0	60.0
1	20.0
2	10.0
3	5.0
5	2.0
7	1.0
9	1.0
13	0.50
15	0.50
Total	100.00

Figure 32. Event tree and density distribtution for TNT.

4.3.6 Propane release

According to Icelandic regulations, no. 984/2000 and 684/1999, it is only allowed to transport 50 kg of liquid petroleum gas, typically propane gas, in cylinders at a time. Larger amounts are strictly forbidden and it is not reasonable to assume that these rules are being broken. Due to this fact it was decided to only investigate possible scenarios from a transport vehicle transporting 50 kg of propane in a cylinder.

There are a number of reasons why propane gas releases from a cylinder and usually a distinction between two types can be made; continuous or instantaneous release. Continuous release occurs if a safety pressure valve has opened due to overheating, resulting in rising pressure inside the cylinder or if an accident causes a minor puncture to the cylinder, flange or valve to be broken in the cylinder. An instantaneous release can happen if the cylinder collapses, mostly due to overheating of the cylinder. If the release happens at a place on the cylinder where the propane is condensed (in the liquid phase) then the flow of propane out of the cylinder can be so great that the whole content might be released within a few seconds so it can be treated as it would be instantaneous.. Figure 15 is a snapshot from a menu box in the software Gasol 2001, version 2.5 which was developed by Räddningsverket (Swedish Rescue Services Agency) in cooperation with the Dept. of Fire Safety Engineering at Lund University, Sweden. The figure shows graphically the various release possibilities for gases and corresponding consequences.

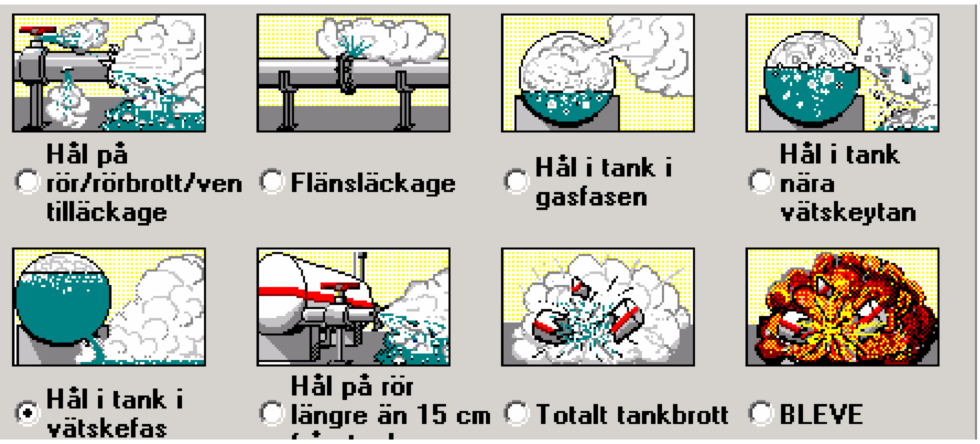

○ Hål på rör/rörbrott/ventilläckage
○ Flänsläckage
○ Hål i tank i gasfasen
○ Hål i tank nära vätskeytan
● Hål i tank i vätskefas
○ Hål på rör längre än 15 cm
○ Totalt tankbrott
○ BLEVE

Figure 33. Various release possibilities for propane. (Räddningsverket 2001)

The quantity of propane that will be released (kg/s) depends mostly on few factors; the size of the hole, placement of the hole (in the gas- or liquid phase), amount of propane in the tank, pressure difference in the cylinder and outside, terrains topography and weather and wind conditions. If there is any ignition source in the area of the damaged cylinder an explosion or a fire might occur. If the ignition happens directly after the propane starts to flow out a **jet fire** will most likely set off. A jet fire is a type of fire when a large flame stretches out, a relatively long distance, from the release source. If the propane flows downstream with the wind a gas cloud might form and if it’s concentration of propane/air mixture is within the flammability region (2-9,5%) it can ignite if it finds an ignition source. If there is no turbulence then the flame will propagate relatively slow, this phenomenon is called **flash fire**. In the presence of turbulence however flames will propagate faster and an explosion might occur, this phenomenon is called **vapour cloud explosion (VCE)**. A so called **BLEVE** (Boiling Liquid Expanding Vapour Explosion) happens only if the cylinder is exposed to heat so that the propane inside starts to boil resulting in higher and higher pressure until the propane instantaneously bursts out from the ruptured cylinder and explodes. Normally a fire ball can be expected to form where the propane burns very quickly as the intensity of radiation is very large (Räddningsverket, 1996)

In Iceland it can be assumed that propane cylinders are equipped with a pressure relief vent to minimise the risk of a fatal explosion. There is however a slight chance that the relief is faulty in such a way that BLEVE might occur. In large tanks there are known cases where the pressure relief vent worked but still resulted in BLEVE as the gas wasn’t released quickly enough to lower the pressure inside the tanks. It has to be concluded that if the pressure relief valve works then BLEVE won't occur, a larger tank must simply be required.

By summing the above information regarding what scenarios are possible from accidents involving propane gas cylinders an event tree, see figure 16, was constructed with 8 possible scenarios.

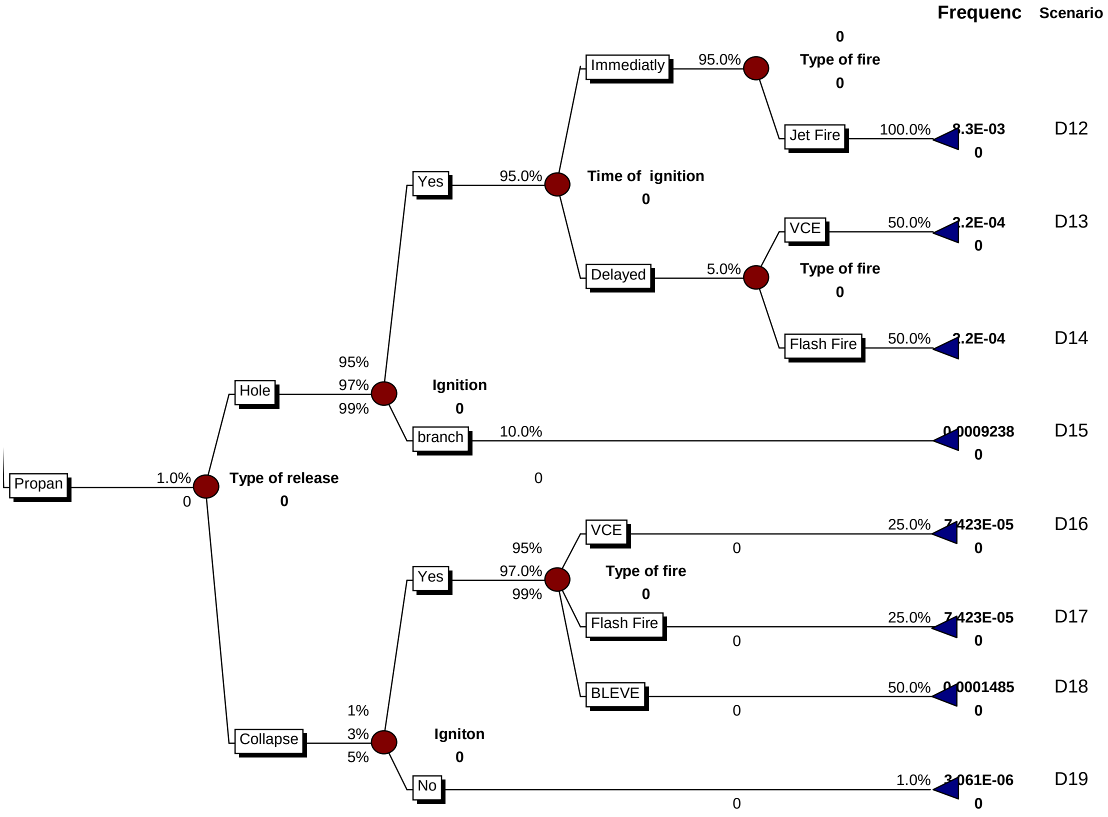


Figure 34. Event Tree for 50 kg. Propane Cylinder.

Above frequencies describe the probability once a dangerous accident involving Propane has occurred. Frequency for BLEVE in a 50kg cylinder was taken from the joint OECD/PIARC research project on the “transport of Dangerous Goods through Road Tunnels” (ERS2). Other probabilities were estimated mostly by using expertise judgement.

4.3.6.1 Jet Fire from a 50 kg Propane Cylinder

By using software called Gasol 2001, version 2. then the length and duration of a jet fire from a 50 kg propane cylinder could be calculated. By assuming that a hole in the cylinder with a diameter of 1-2 cm occurs either in the gas or liquid phase then the software estimates the length of a jet fire to range from 4.6 to 14.2 meters long lasting for 716 to 21 seconds respectively, see input data in Appendix B. The former case describes a 1 cm hole in the gas phase and the latter when there is 2 cm hole near the liquid surface.

A jet fire is most likely going to happen as a direct consequence from an accident or as a secondary consequence from a nearby fire. Jet fire might thus happen almost directly after an accident or many minutes after an accident. In the worst case scenario, the jet fire stretches out 14.2 meters causing 3 degrees burns up to 18 meters and 8 meters perpendicular from the fire source, see Figure 35.

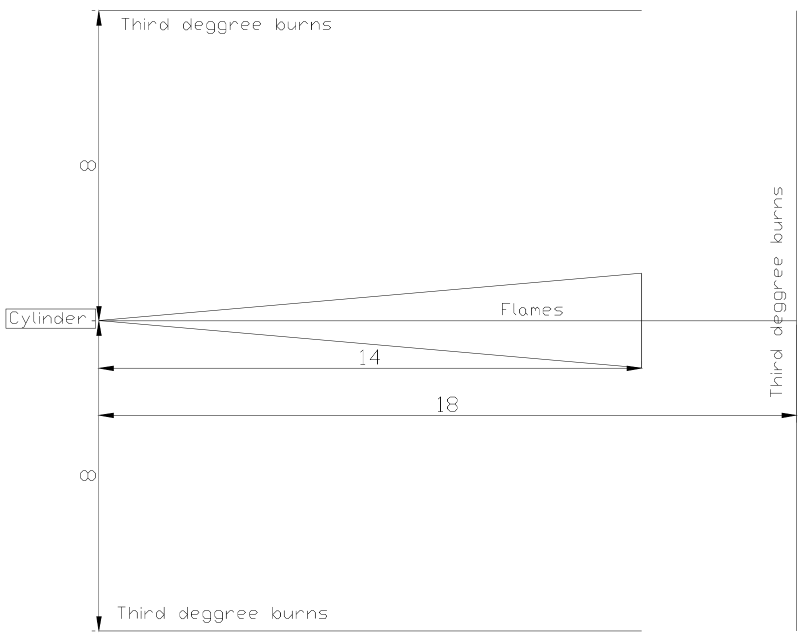


Figure 35. Jet fire from a 2 cm hole near the liquid surface.

A single queue of vehicles that stretches further than 18 meters would count about 3 vehicles and if there are 2.5 person per vehicle then that would most likely cost the life of 7-8 persons. If the jet fire would however point towards the tunnel ceiling then third degree burns could be expected within 8m radius from the cylinder and that would have caused the probable death of 2-5 persons.

In the “best” case scenario, third degree burns are expected 5.3 meters away from the cylinder and 2 meter away perpendicular from the cylinder. This would probably result in the death of 0-3 persons.

There are however as one can imagine many uncertainties involved:

- Will a queue form before the jet fire starts?
- How many persons are in the risk zone when it starts?
- Towards which point will the jet fire direct to?

To get some rough estimation on these and other questions a cause consequence tree was constructed, see figure below.

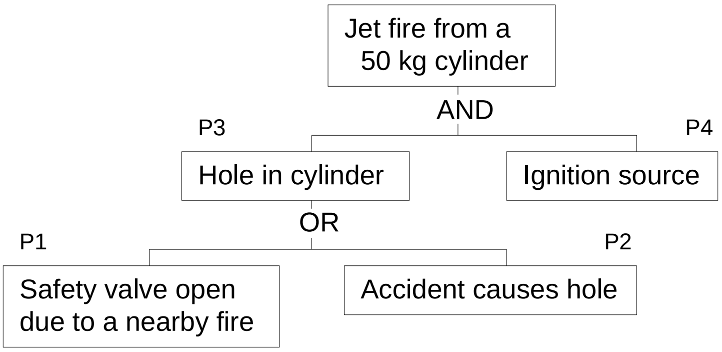


Figure 36. Fault tree for a jet fire in a a kg propane cylinder.

Because cylinders storing gas under pressure are built to tolerate great pressure it can be assumed that a massive force is needed to puncture a hole or break a flange of a gas cylinder. It can therefore be assumed that the majority of holes are caused by an external heat source causing the safety valve to open. This means that there have to pass minutes before a jet fire starts and by the time it starts, people will have already evacuated in most cases. It was estimated that in about 90 % of cases the root cause of a jet fire would be because of safety valve had opened due to an external fire. This means that minutes, typically 10-30 minutes will pass before the jet fire starts and by that time it can be concluded that all persons capable of evacuating have evacuated.

Based on this information a density distribution was estimated as figure 18 shows. This distribution applies to scenario D12 in Figure 34.

Fatalaties	P (%)
0	90.0
1	6.0
2	0.9
3	0.8
4	0.7
5	0.6
6	0.5
7	0.4
8	0.1
Total	100.0

Figure 37. Estimated density distribution for the consequences of a jet fire.

4.3.6.2 Flash fire

By studying output data from Gasol (Appendix B) involving flash fire, results were as follows:

1 cm hole in the gas phase:
Vapour Cloud dimensions (B*L): 1.9 m * 17.2 m
Third degree burns (B*L): 5.6 m * 20.1

2 cm hole near liquid surface:
Vapour Cloud dimensions (B*L): 3.1 m * 5.0 m
Third degree burns (B*L): 6.6 m * 13.2

Tank collapse:
Vapour Cloud dimensions (B*L): 7.2 m * 15.0 m
Third degree burns (B*L): 16.5 m * 35.7 m

The worst case here would be if a dense vehicle queue is downstream from the accident when a tank collapse occurs. A 36 m long single queue would count approximately:

36 m/ (6m/vehicle) = 6 vehicles

Assuming that 2.5 persons are in each vehicle gives, about 15 persons might die as a result of a flash fire. The smallest flash fire would probably result in the death of maximum:

2 vehicles*2.5 persons/vehicle = 5 persons.

To get some rough estimate on which effects a flash fire might have on humans in the tunnel a similar procedure was use as for the jet fire, that is a cause consequence tree was constructed to get some idea of what could be the cause of a flash fire, hence what time is likely to pass before it occurs.

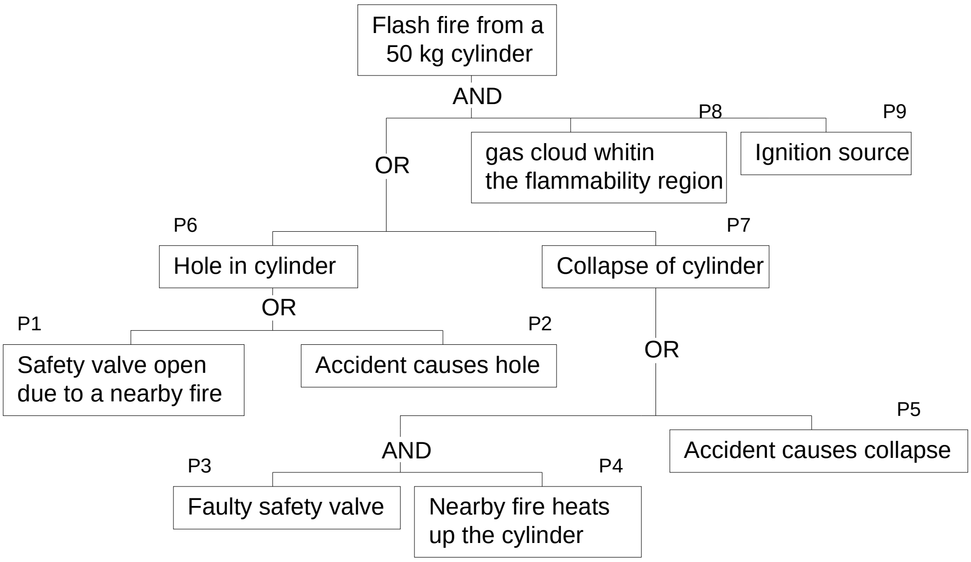


Figure 38. Cause consequence tree for a flash fire.

By using the same logic here as for the jet fire one can conclude that causes of propane release are mostly because of a nearby fire and therefore almost all will have evacuated because of that fire. Collapse of a cylinder is also very unlikely because as Figure 38 shows, a faulty safety valve is one of the conditions for a collapse and it is very unlikely that an accident causes an instantaneous collapse. In other words a flash fire will occur almost instantaneously (due to P2 or P7) or minutes after the accident occurrs (due to a nearby fire). It is also assumed that a nearby fire is the most likely cause for a flash fire. Assuming that a nearby fire is the most likely cause for a flash fire then it can be concluded that everyone capable of evacuating will have evacuated when the flash fire occurs as it takes less than a minute to evacuate 36 m (assuming 0.7 m/s walking speed) and according to table 3 in Chapter 4.4.6.1 the reaction and response time can be estimated to be 50 seconds. Awareness time would be from 0 to 1-5 minutes, depending on when vehicles arrive at the scene. Evacuation time can therefore roughly estimated to be on the range 2-7 minutes. Experience with indicates that a time delay for a flash fire is typically on the range 20-30 minutes (Wolf, n.d.).

Based on the above crude assumptions it can be concluded that is very likely that everyone capable of evacuating will have evacuated when the flash fire occurs. Density distribution (Figure 39) to estimate fatalities due to flash fire was constructed.

Fatalaties	P (%)
0	60.0
1	20.0
2	10.0
3	5.0
5	2.0
7	1.0
9	1.0
13	0.50
15	0.50
Total	100.00

Figure 39. Estimated density distribution for the consequences of a flash fire.

4.3.6.3 Vapour Cloud Explosion

As mentioned earlier a vapour cloud explosion occurs if burning of the gas is subjected to turbulence causing the flame front to propagate so fast that an explosion occurs. Persons are therefore not only exposed to heat as in the flash fire but also from effects from the explosion that is a shock wave, flying fragments et cetera. Consequences from a vapour cloud explosions can therefore be assumed to be worse then for the flash fire. Using software called RMP, see results in appendix B, the distance from the explosion to an overpressure of 100 kPa was estimated to be 60 m. This estimation is based on an explosion in the open. A vapour cloud explosion inside a tunnel would probably be more severe as the explosion can only vent out through the tunnel openings. However comparing these results to the results from the 50 kg TNT explosion these seem to be rather conservative, but to be able to say for sure, thorough theoretical studies or testing would be needed which are outside the scope of this thesis.

Apart from the top event a cause consequence tree for the vapour cloud explosion is very similar to the fault tree for the flash fire. It is therefore likely that vapour cloud explosion will take place almost instantaneously (P2 or P7 in Figure 38) or minutes after an accident has occurred (due to a nearby fire). A worst case scenario would thus be dense queue when the evacuation process has not started, upside and downstream from the source. This can be calculated to be:

Total length of vehicle queue: 60+60 = 120 m
Length that each vehicle uses in a queue: 6 m/ vehicle
Amount of vehicles: 120m/6 m /vehicle = 20 vehicle
Amount persons per vehicle: 2.5
Amount of persons: 20 vehicles * 2.5 persons/vehicle = 50 persons.

However considering the fact that typically 20-30 minutes will pass before the Vapour Cloud Explosion occurs then it is most likely that everyone already has evacuated.

Based on above assumptions a density distribution, Figure 40, to estimate fatalities due to Vapour Cloud Explosion was constructed.

Fatalaties	P (%)
0	60.0
1	20.0
2	10.0
3	5.0
5	2.0
8	1.0
15	1.0
25	0.50
50	0.50
Total	100.00

Figure 40. Estimated density distribution for the consequences of a VCE.

4.3.6.4 BLEVE

Consequences from a BLEVE were also calculated with Gasol 2001, version 2.5. It was assumed that consequences from a vapour cloud explosion would be similar as they both burn vigorously. Main results from Gasol were as follows:

Mass released was 49.4 kg.
The diameter of the BLEVE was 23.01 m.
The BLEVE lasts for 2.3 s.
The BLEVE is found to be 17.26 m over the ground.
Distances from the BLEVE where third degree burns are to be expected was found to be 13 m.

It is not a simple task to interpret these results with regard to the fact that the accidents occurs inside tunnels. But as a first approximation it was decided to assume that BLEVE would cover the same volume inside as outside: Assuming that the BLEVE's fire ball is spherical and using the average cross area of the tunnel the BLEVE inside tunnel could be calculated to be as long as:

Volume of BLEVE outside: $V = \frac{pD^3}{6} = \frac{p \cdot 23.01^3}{6} = 6379\ \mathrm{m}^3$

Equivalent length of BLEVE inside the tunnel: $L = \frac{V}{A} = \frac{6379}{58} = 110\ \mathrm{m}$

A 110m is therefore the length of the BLEVE but effects from flying objects, radiation from the BLEVE and the shock wave that the BLEVE creates make the length of the deadly zone to stretch even further. By adding the distance from the BLEVE where third degree burns were found to be the deadly zone could be stretched to be 110+13+13 = 139m or 69.5m in each direction. Effects from flying objects and shock waves aren't considered due to lack of tools.

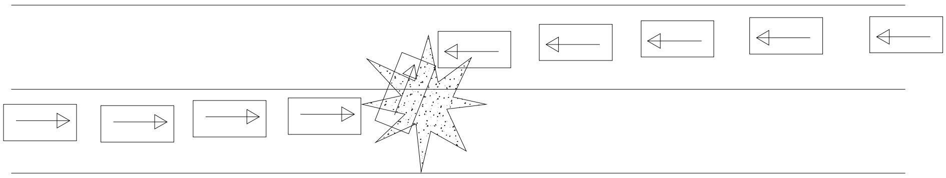


Figure 41. Vehicles at risk when BLEVE occurs.

Assuming that there are dense vehicle queues both upstream and downstream and that the evacuation process hasn't started, see figure 21, then the worst case scenario can be calculated as follows.
Total length of vehicle queue: 139m.
Length that each vehicle uses in a queue: 6m/ vehicle.
Amount of vehicles: 139/6 = 23 vehicles.
Amount persons per vehicle: 2.5 persons/vehicle.
Amount of persons: 23 * 2.5 = 58 persons.

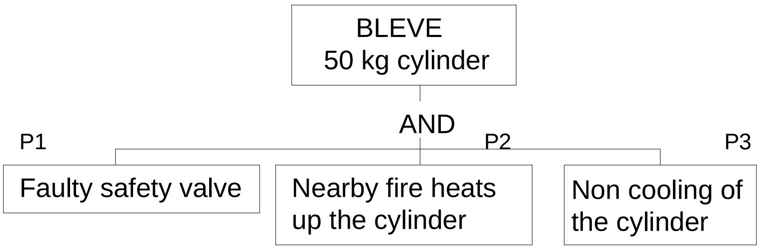


Figure 42. Fault tree for a BLEVE

As Figure 42 indicates then a nearby fire is one of the conditions for a BLEVE to occur. The time that elapses until BLEVE occurs is depended on the heat that the cylinder receives but according to experience from accidents involving BLEVE then it can be estimated that around 20-30 minutes will elapse before BLEVE occurs. However these accidents involve larger quantities, from few thousands kg to hundreds of tons of propane and it's quite reasonable to assume that it might take less time for a 50 kg cylinder (Wolf, n.d.). A nearby fire would start the evacuation process quickly (at least downstream from the fire) and if a person walks 0,7 m/s then it would take that person about a minute and a half to walk 69.5 m. It can thus be assumed that almost everyone will have evacuated further then 69.5 meter once the BLVEVE occurs. In few words it is assumed that most likely will a BLEVE in Hvalfjörður Tunnel cause few if any deaths. There is however uncertainty about the time delays for a BLEVE to occur and there is also uncertainty about the pressure build up inside the tunnel.

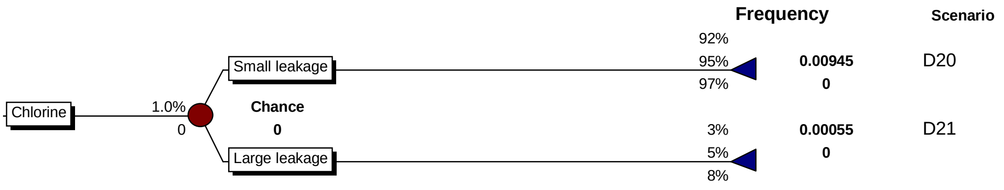
Based on these assumptions a density distribution to estimate fatalities due to BLEVE was constructed.

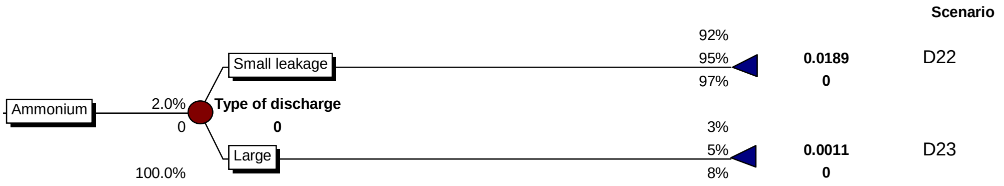
Fatalaties	P (%)
0	60.0
1	20.0
2	10.0
3	5.0
5	2.0
10	1.0
20	1.0
35	0.50
58	0.50
Total	100.00

Figure 43. Estimated density distribution for the consequences of BLEVE.

4.3.7 Chlorine release and ammonia release

As the likelihood of a chlorine or ammonia release is very low (very few vehicles) it was decided to calculate only the worst case scenario. The worst case scenario would be an immediate release from a tank, producing a deadly cloud mowing in the same direction and velocity as the wind inside the tunnel. Small leakage was not regarded as lethal. Everyone meeting the cloud would thus have no chance of survival. To calculate the effects the same model to calculate number of persons at risk during a fire scenario was used, except that here everyone in the risk zone were assumed to die. Event tree for these scenarios is shown below.





4.3.8 Summary

Table 7 summarizes results from above scenarios.

Table 7. Summarized results from the Monte Carlo simulations

Scenario no.	Consequences				Frequency per year			
	Minimum	Maximum	Average	std.dev	Minimum	Maximum	Average	std.dev
A1	1.0	1.0	1.0	0.0	5.4E-02	1.4E-01	9.9E-02	1.0E-02
B1	0.0	0.0	0.0	0.0	1.1E-03	3.2E-01	1.3E-01	6.9E-02
B2	0.0	34.1	0.0	0.4	1.8E-03	4.4E-01	1.9E-01	9.9E-02
B3	0.0	118.0	4.6	10.1	2.2E-05	8.7E-03	2.9E-03	1.6E-03
C1	0.0	0.0	0.0	0.0	2.0E-02	4.9E-02	3.3E-02	3.5E-03
C2	0.0	116.2	8.4	12.1	2.5E-03	7.1E-03	4.4E-03	6.5E-04
C3	0.0	101.9	10.7	12.4	1.6E-04	8.7E-04	4.2E-04	1.2E-04
C4	0.0	112.8	11.0	12.3	1.6E-04	8.7E-04	4.2E-04	1.2E-04
D1	0.0	79.4	6.8	7.0	3.7E-05	3.6E-04	1.6E-04	5.5E-05
D2	0.0	59.8	6.3	7.0	5.6E-04	2.5E-03	1.4E-03	2.6E-04
D3	0.0	0.0	0.0	0.0	3.1E-04	1.5E-03	8.5E-04	1.6E-04
D4	0.0	79.4	6.8	7.0	1.4E-05	2.9E-04	9.4E-05	4.4E-05
D5	0.0	67.0	6.6	7.1	2.6E-05	4.7E-04	1.7E-04	7.2E-05
D6	0.0	0.0	0.0	0.0	1.9E-05	2.4E-04	9.0E-05	3.6E-05
D7	0.0	79.4	6.8	7.0	9.5E-09	1.7E-04	4.8E-05	3.0E-05
D8	0.0	79.4	6.8	7.0	3.0E-09	9.9E-05	2.1E-05	1.6E-05
D9	0.0	0.0	0.0	0.0	8.5E-10	1.7E-05	3.6E-06	2.9E-06
D10	0.0	15.0	1.0	2.0	6.6E-07	9.3E-06	3.8E-06	1.5E-06
D11	0.0	0.0	0.0	0.0	9.5E-06	4.5E-05	2.6E-05	4.6E-06
D12	0.0	8.0	0.2	0.9	9.6E-06	4.2E-05	2.5E-05	4.2E-06
D13	0.0	50.0	1.3	4.3	2.5E-07	1.1E-06	6.6E-07	1.1E-07
D14	0.0	15.0	1.0	2.0	2.5E-07	1.1E-06	6.6E-07	1.1E-07
D15	0.0	0.0	0.0	0.0	1.1E-06	4.7E-06	2.8E-06	4.7E-07
D16	0.0	50.0	1.3	4.3	3.4E-08	5.5E-07	2.2E-07	9.5E-08
D17	0.0	15.0	1.0	2.0	3.4E-08	5.5E-07	2.2E-07	9.5E-08
D18	0.0	58.0	1.4	5.2	6.8E-08	1.1E-06	4.5E-07	1.9E-07
D19	0.0	0.0	0.0	0.0	1.4E-09	2.3E-08	9.3E-09	3.9E-09
D20	0.0	0.0	0.0	0.0	1.1E-05	4.7E-05	2.9E-05	4.8E-06
D21	0.0	59.8	6.8	6.9	5.1E-07	3.6E-06	1.7E-06	5.2E-07
D22	0.0	0.0	0.0	0.0	2.2E-05	9.2E-05	5.7E-05	9.5E-06
D23	0.0	59.8	6.8	6.9	1.0E-06	7.4E-06	3.3E-06	1.0E-06

To help one to understand the magnitude of uncertainty Figure 44 was constructed from Table 7. Note that scenarios having zero consequences are the ones where, for examples fire was put out with extinguishers.

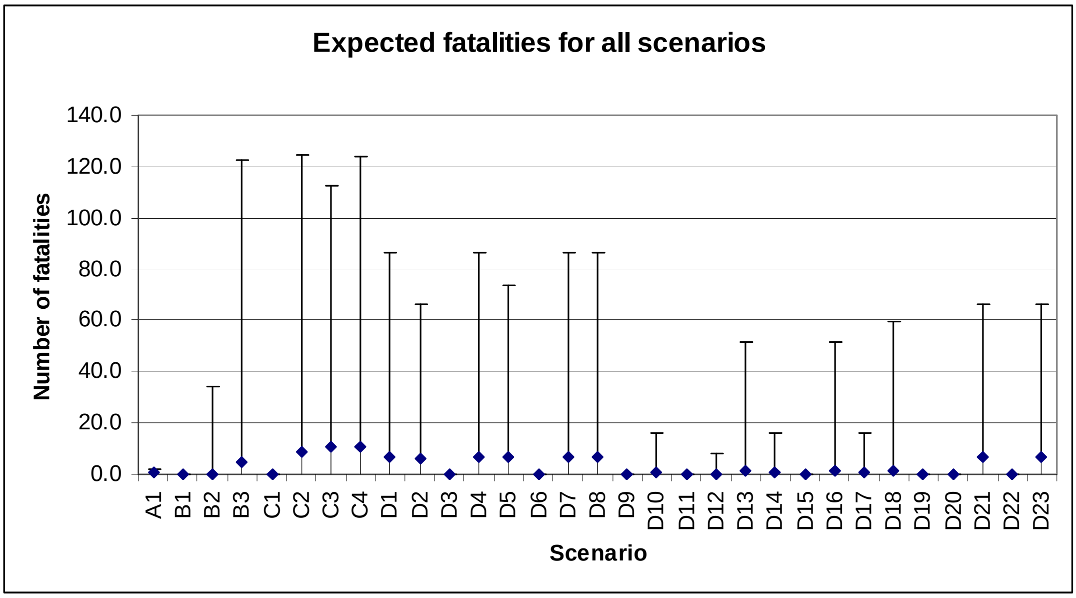


Figure 44. Results from the Monte Carlo Analysis, minimum, average and maximum fatalities for each scenario.

As both the above figure and table show clearly how uncertainty these results are. Trying to reduce this uncertainty is hardly possible because there is no way to estimate where and when accidents occur which plays a huge role for most of the scenarios.

5 RISK EVALUATION, INDIVIDUAL AND SOCIETAL RISK

5.1 Appropriate risk criteria for the Hvalfjörður Tunnel

Transport activities of dangerous goods have caused special problems when it comes to societal criteria, mostly because the longer the road segment being considered thus bigger will the risk be. This has been the main reason for why authorities in Holland for instance only use individual risk criteria. Individual risk can be expected to be little because the risk of an accident occurring precisely in front of someone's house is very little. The societal risk can however be extensive because dangerous goods accident can lead to severe consequences. In Hong Kong a societal risk criteria for industrial activity was used as a criteria for transport of chlorine. This was thought reasonable because the transportation was assumed to benefit in same way as if it were a single potential dangerous activity.

In road tunnels there are however not only vehicles transporting dangerous goods that pose risk for severe consequence but also heavy vehicles transporting ordinary goods and even ordinary passenger vehicles. Looking at Hvalfjörður tunnel as a single potentially dangerous activity is attempting, especially when having in mind that the tunnel has without any doubt brought many benefits. Looking at only transportation of dangerous goods as the problem is, according to the authors own opinion, like looking at the problem with the blind eye. If one wants to use this as a criterion for tunnel safety, it should include all traffic because all vehicles (especially the heavy ones) can cause similar consequences as if they were carrying dangerous goods. Even if transport of dangerous goods could be shown to satisfy criteria for such transportation then they still are a part of the total risk, therefore if the risk can be decreased by eliminating transportation of dangerous goods it should be considered.

In the Øresund Bridge (both bridge and tunnel) risk criteria were related to the risk persons using road or rail (with best safety) would normally be exposed to. Considering the benefit brought to persons using the bridge it was accepted that the risk might be little higher than the criteria used. It must though be considered that increasing the safety standard afterwards in such superstructure as the bridge is, might be extremely difficulty and costly Using the today situation as a criteria is therefore questionable because in the future, safety on roads might have improved greatly making the bridge fail to live up to future standards. (Davidsson, et al., 1997).

Comparing the risk in Hvalfjörður Tunnel versus Hvalfjörður road is appealing because decreasing risk must be better than doing nothing. The same is valid here as for the Øresund Bridge, will the tunnel live up to future standards? One might also ask if its alright to use this unit, shouldn't roads be equally risky per km? It is known that accidents occur more often on certain spots than other. Through registry of accidents there is however an ongoing system to identify these spots and if possible eliminates them. Hot spots are therefore not automatically accepted by the authorities or by the public. Shouldn't it also be a sure thing if a particular road is shortened by factor x then it should be at least x times safer? It seems therefore reasonable to conclude that road segments should be equally safe if possible.

5.1.1 Short overview over units used and conversion factors for them

Traditionally information regarding traffic and risk criteria are given in different units. In road traffic frequency is often given as per vehicle km but sometimes as per person km to enable fair comparison with other industries like train or flights. It is also a well known fact that flight accidents are most likely during take off or landing. That's why the unit per trip is more relevant to use in comparison with risk of flying than travelled km.

To exemplify relationships between those units it was decided to calculate conversion factors between those units, (average frequency of vehicle fire in Hvalfjörður Tunnel was used).

AADT: 3600 vehicles/day
Length of tunnel: 5.77km
Traffic work per year: 3600 vehicles/day * 365 days * 5.77km =7,581,780 vehicle km or 7,581,780 vehicle km/year
Average number of passenger per vehicle: 2.54 passenger/vehicle
Person km/year: 2.54 passenger/vehicle * 7,581,780 vehicle km/year = 19,257,721 person km/year
Frequency of vehicles fire per million vehicle km: 0.0453 fires/(10^6 vehicle km)

Conversion between different units can now be calculated as follows:

Conversion to yearly frequency:

0.0453 fires/(10^6 vehicle km)* 7,581,780 vehicle km/year = 0.343 fire per year

Conversion to frequency per person km:

0.0453 fires/(10^6 vehicle km)/(2.54 persons/vehicle) = 0.0178 fires/(10^6 persons km)

Converting frequency to frequency per trip:

0.0453 fires/(10^6 vehicle km)*5.77 vehicle km/trip = 0.261 fire/(10^6 trip)

Conversion factors between those units can now calculated, see results in Table 8.

Table 8. Conversion factors (multiplication)

From	To			
	Per million vehicle km	Per year	Per million person km	Per million trips
Per million vehicle km	1.0000	7.5818	0.3937	5.7700
Per year	0.1319	1.0000	0.0519	0.7610
Per million person km	2.5400	19.2577	1.0000	14.6558
Per trip	0.1733	1.3140	0.0682	1.0000

Converting from 1 million to 100 or 1000 million km is simply done by multiplying the unit with that ratio between those units, for example converting frequency of vehicles fire per million vehicle km to frequency of fire per 100 million vehicle is calculated as follows:

0.0453 fires/(10^6 vehicle km) *100/100 =4.53 fires/(10^8 vehicle km)

5.1.2 Individual risk criteria

The risk of being hit by lightning is often given as 10^{-7}/year. This risk level is therefore often taken as the level were no further actions need to be taken. In other words this is the level were risk is being regarded as negligible. Davidsson, et al.(1997), proposed an individual risk criteria. According to this criterion, risk can be tolerated if it is less than 10^{-5}/year but risk higher than this needs actions, regardless of what they might cost. Risk between 10^{-5} and 10^{-7} per year should lowered if it can be shown reasonably practicable. This criterion is also being referred to as DNV criteria. This criterion represents the average individual risk and in order to calculate this number, the number of persons exposed to the risk must be estimated.

Using same methodology as was used in the Øresund bridge project, that is using the today fatality frequency on the road the individual risk should not be more than 1.3 fatal accidents per 100 million vehicle km or 0.51 per 100 million person km. This number reflects the fatality rate in Hvalfjörður Road over the years 1993-1997. For comparison, the fatality rate on highways in Faroe Islands over the period 1991-2000 was 1.4 fatal accidents per 100 million vehicle km.

Comparing the risk of using the old road, in the units per trip, an individual risk criterion was calculated to be $7.8*10^{-7}$ or 78 fatal accident per 100 million trips. This criteria, as discussed above, should however be seen more as informative for how much the risk has been lowered.

In Norway an acceptance risk criteria for individual risk for driving on roads was found (NFV-Seminar, 2002). This risk criterion for urban tunnel systems was set to total 0.2 fatal accidents per 100 million person km. This number is quite low compared to the historic level of 0.6 fatal accidents per 100 million person km for all traffic deaths in Norway (1991-2000), (Amundsen, et al., 2002). Using 0.2 fatal accidents seems therefore not reasonable to use in rural tunnels so it was decided to use 0.6 fatal accidents per 100 million person km.

Summary of possible individual risk criteria:

1. Less than 10^{-5} per year (DNV criteria).
2. Less than 78 fatal accidents per 100 million trips (Using Hvalfjörður Road).
3. Less than 1.3 per 100 million vehicle km (Hvalfjörður road)
4. Less than 0.6 fatal accident per 100 million person km (Norway 1991-2999)

5.1.3 Societal risk criteria

Societal Risk can also be interpreted in many ways depending on what units for the probability are used. Here it was decided to look at societal risk in two different units; as frequency per year in the tunnel and as frequency per 1000 million (thousand millions) person km. The first one interprets the risk as an activity in the society while the second one enables one to compare the risk to other transport media, like traffic on highways, flight traffic et cetera.

Criteria, in the unit as risk per year, found in the literature, refer most to dangerous industrial activities. Application of such criteria is questionable but was however used in Hong Kong for example. Figure 45 shows criteria from HSE and DNV, Davidsson, et al.(1997). Notice that the tolerable criterion from DNV equals the negligible criteria from HSE. All those figure have a slope factor equal to –1.

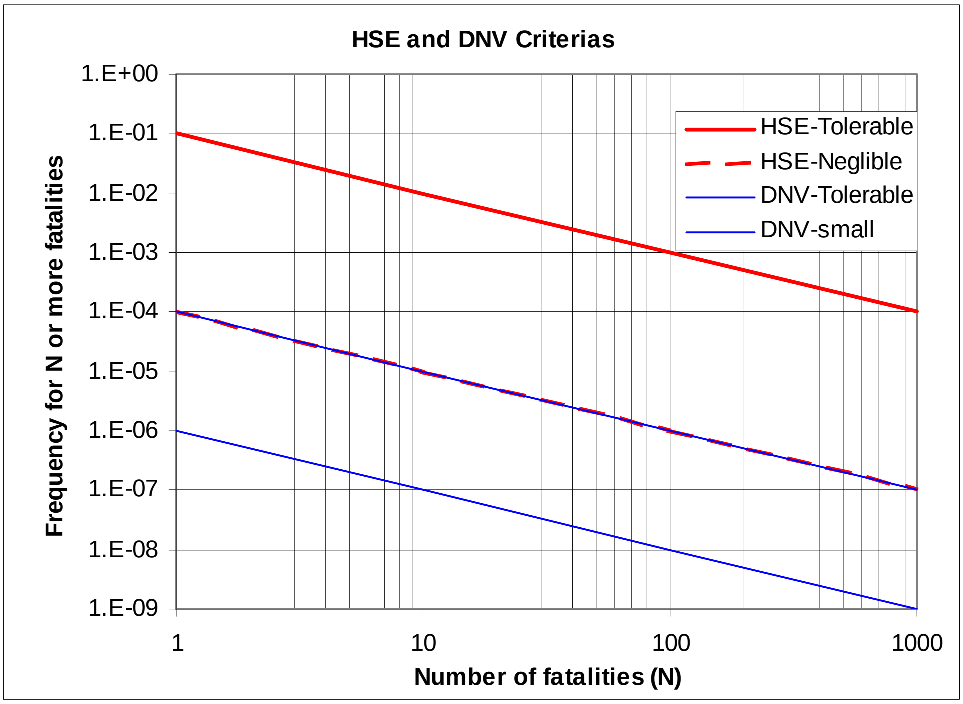


Figure 45. HSE and DNV criteria for societal risk, Davidsson, et al.(1997).

A FN curve is said to lie in the so called ALARP region if it lies between the HSE criteria of tolerable and negligible criteria. ALARP stands for “As Low As

Reasonably Practicable" and means that risk needs only to be reduced if the approach can be shown to be reasonably practicable.

Societal risk criteria especially constructed for traffic were not easily obtainable. One criteria was however found proposed by the Statens Vegvesen i Oslo (The Public Road Administration in Oslo), (NFV-seminar, 2002). This criterion was measured against the Björvika Tunnel system in Norway which is situated in an urban area. Historical FN curve for a typical highway road in Norway was also presented. These curves are shown in the unit of frequency of fatal accidents per thousand million person km.

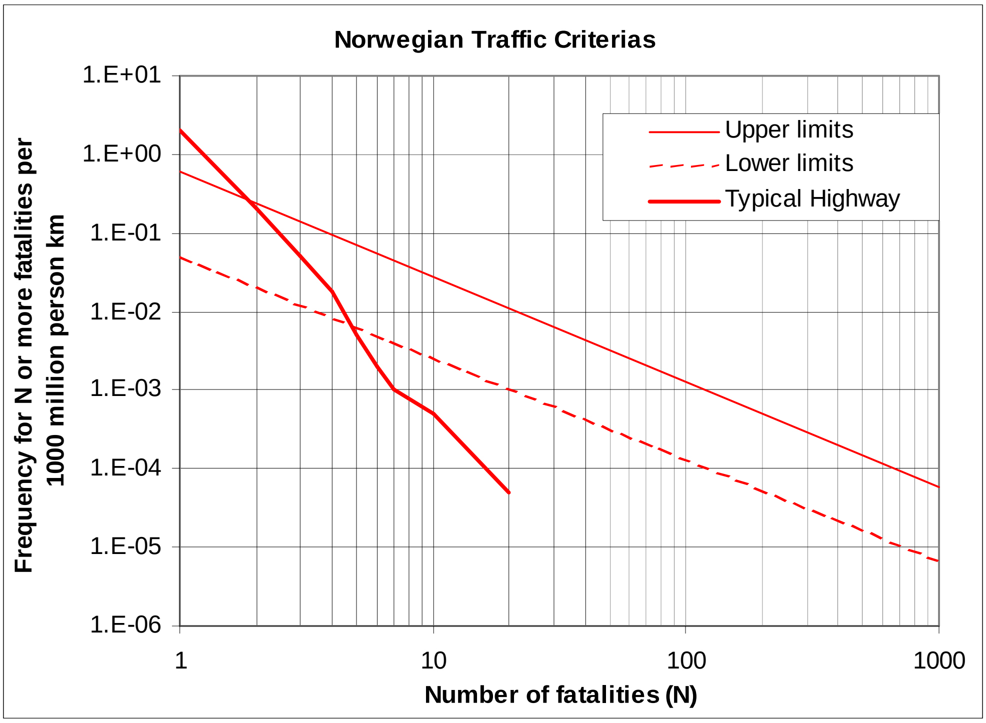


Figure 46. Norwegian criteria, NVF-seminar (2002)

To calculate the expected value from a FN curve, the absolute frequency for all fatalities (for example: N = 1, 2, 3..1000 fatalities) must first be calculated and then these must be multiplied with the respective number of fatalities. The expected value for the Norwegian upper limit criteria was found to be 1.98 fatalities per 1000 million person km.

Comparing this number to the historic level of 6 fatalities per 1000 million person km it can be concluded that this criteria is rather conservative (3 times) but reflects perhaps the long term goal of reducing traffic accidents.

More reasonable criteria should either be based on historical data like shown for the typical highway or by constructing a criterion bearing few principles in mind:

- The criteria should reflect the publics will to avoid catastrophes (slope exponent steeper than –1).

- It should be reasonable in other words it should lead to safety features which are according to the ALARP principle (As Low as Reasonably Possible).
- The expected fatality rate should be at least lower than the historic level to reflect the government's policy of reducing fatal traffic accidents.

Bearing the above principles in mind a criterion was constructed with a starting point of 6 fatalities and a exponent slope equal to –2. The expected fatality rate using these numbers was found to be 6.4 per 1000 million person km which is slightly higher than the historic level in Norway.
Comparison of this new proposed criterion to the Norwegian criteria is shown in Figure 47.

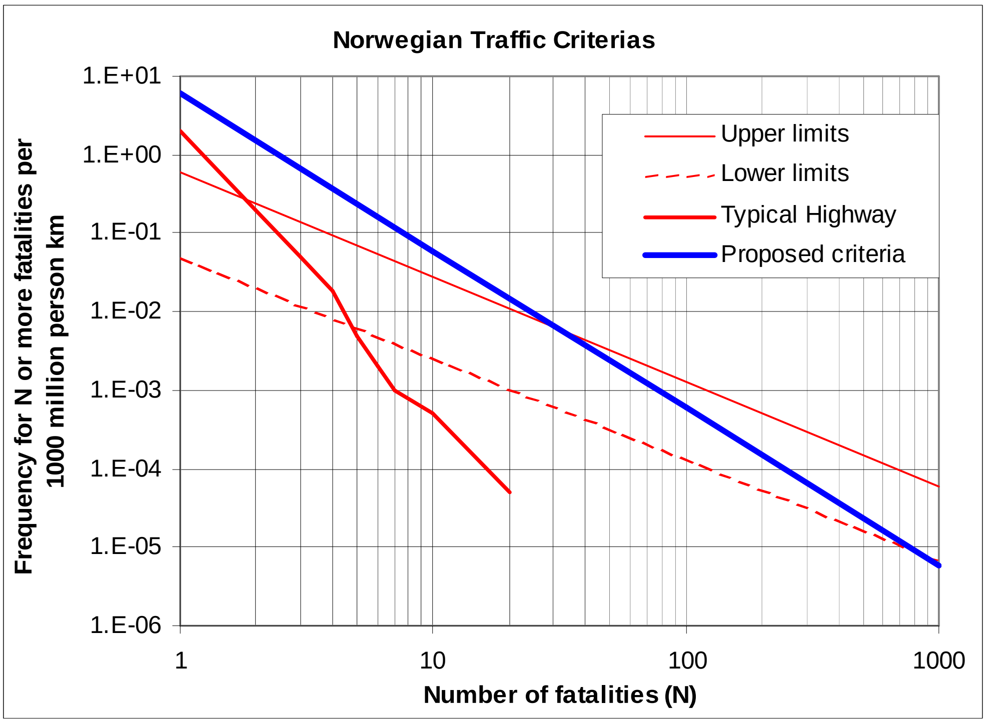


Figure 47. Proposed criteria compared to Norwegian criterias.

The purpose of constructing this new criterion is more to illustrate how such curve can be constructed. Establishing a criterion is not an easy task as there are so many aspects to consider. Should a criterion reflect current status or future and how reasonable is it to fulfil these criteria? This proposal should thus be taken as a first step of many in a process where these aspects are examined and debated.

5.2 Individual risk

The population used to calculate average yearly individual risk (criteria no. 1) was taken as 30,000 people or the same number as was used in the VST fire risk assessment (1999). Table 9 shows individual risk in Hvalfjörður Tunnel compared to the suggested criteria. All risks are included.

Table 9. Different individual risk critera´s compared to individual risk in Hvalfjörður Tunnel.

Criteria no.	Individual criteria's	Risk of fatality per	Average risk	5-95% confidence interval	Risk passes criteria
1	1.0E-05	year	5.7E-06	*(2.8E-06 - 1.4E-05)*	Yes
2	78	100 million trips	13	*(6.3 - 31.0)*	Yes
3	1.3	100 million vehicle km	2.3	*(1.1 - 5.4)*	No
4	0.6	100 million person km	0.9	*(0.4 - 2.1)*	No

Risk criteria 1 and 2 represent the tunnel as an object in the society while 3 and 4 represent the risk as per travelled km, thus allowing comparison to other roads and transport medias. According to these criteria, risk might be accepted or denied depending on which units are used to represent the risk. Corresponding average individual risk where collisions are excluded can be calculated from Table 13 to be:

$0.073/30{,}000=2.43*10^{-6}$ which can be compared to $1.5*10^{-6}$ in the VST fire risk Assessment.

As the confidence interval shows, uncertainty is great.

Results from a risk analysis for an urban tunnel, Björvika, where found in NFV-seminar (2002), see Table 11. Comparing these results to the results for Hvalfjörður Tunnel in Table 10 is interesting because risks in Björvika tunnel are much smaller . The Annual Daily Traffic in Björvika is 90,000 vehicles compared to 3,600 vehicles in Hvalfjörður Tunnel. A number of reasons might however explain this difference:

- Distance between emergency exits in Björvika varies between 150-300 meters compared to no emergency exits in Hvalfjörður Tunnel.
- Models to quantify risks are not the same.
- Accident rates are often lower in urban areas than rural.

Table 10. Individual Risk in Hvalfjörður Tunnel (average risk).

Scenario	**Expected number of deaths per 100 million person km**	**Percentage of total risk**
Collisions	0.51	58%
Passenger vehicle fire	0.075	8%
Heavy vehicle Fire	0.24	27%
Petrol Tanker fire	0.064	7%
TNT	0.000019	0.002%
LPG	0.000043	0.005%
Chlorine	0.000059	0.007%
Ammoniak	0.000118	0.01%
Total	**0.89**	**100%**

Table 11. Individual Risk in Björvika Tunnel (NFV-seminar, 2002).

Scenario	Expected number of deaths per 100 million person km	Percentage of total risk
Collisions	0.100	76%
Passenger vehicle fire	0.008	6%
Heavy vehicle Fire	0.019	14%
Fire in installation equipment	0.001	1%
Dangerous goods accident	0.004	3%
Total	**0.13**	**100%**

It is also interesting to notice from Table 10 that even though transport of petrol is only about 0.2% of the total traffic, their share in the total risk is 7%. Heavy vehicles are also about 5.7% of the total traffic but their share is 27% of the total risk.

Comparing individual risk to other transport medias is shown in Table 12. This table is also interesting because it shows that the tunnel is actually very safe in the units per trip. Travelling through Hvalfjörður Tunnel is actually:

7.8/1.3 = 6 times safer than using the Hvalfjörður Road and
2.8/1.3 = 2 times safer than travelling by an airplane.

Comparison of risk in the unit per person km travelled is however not in favour of the tunnel in all cases.

Table 12. Comparison of risk in Hvalfjörður Tunnel to historic levels for other transport medias in Norway (1991-2000), adopted from Amundsen, et al. (2002).

	Fatalities per trip	Frequency per 100 million person km
Hvalfjörður Tunnel	1.30E-07	0.89
Hvalfjörður Road	7.80E-07	0.51
Flying	2.80E-07	0.26
Train		0.11
Ferries		0.06
Roads		0.6
Tunnels		0.41
landslide areas		0.37

However it must be noted that comparing the risk of driving to other risks is always dangerous because there are so many other aspects which deal with concepts like perception and benefit, see Chapter 2.3.2. The purpose of the above comparison is more to illustrate that it is possible to present risk in various ways. The risk of travelling through Hvalfjörður Tunnel seems quite low when measured in the unit per trip, but is not as safe when measured in the unit per km!

5.3 Societal risk

Societal Risk can also be interpreted in many ways depending on what units for the probability are used. Here it was decided to look at societal risk in two different ways; as yearly frequency in the tunnel and as frequency per 1000 million (thousand millions) person km. As was noted before the first one interprets the risk as an object in society while the second one enables one to compare the risk to other transport media, like traffic on highways, flight traffic et cetera. Note risks due to collisions are not included in the societal risk curve (FN) as they were only evaluated in the case of individual risk. Societal risk for Hvalfjörður Tunnel compared to risk criteria suggested in chapter 5.1.3., is shown in Figure 48.

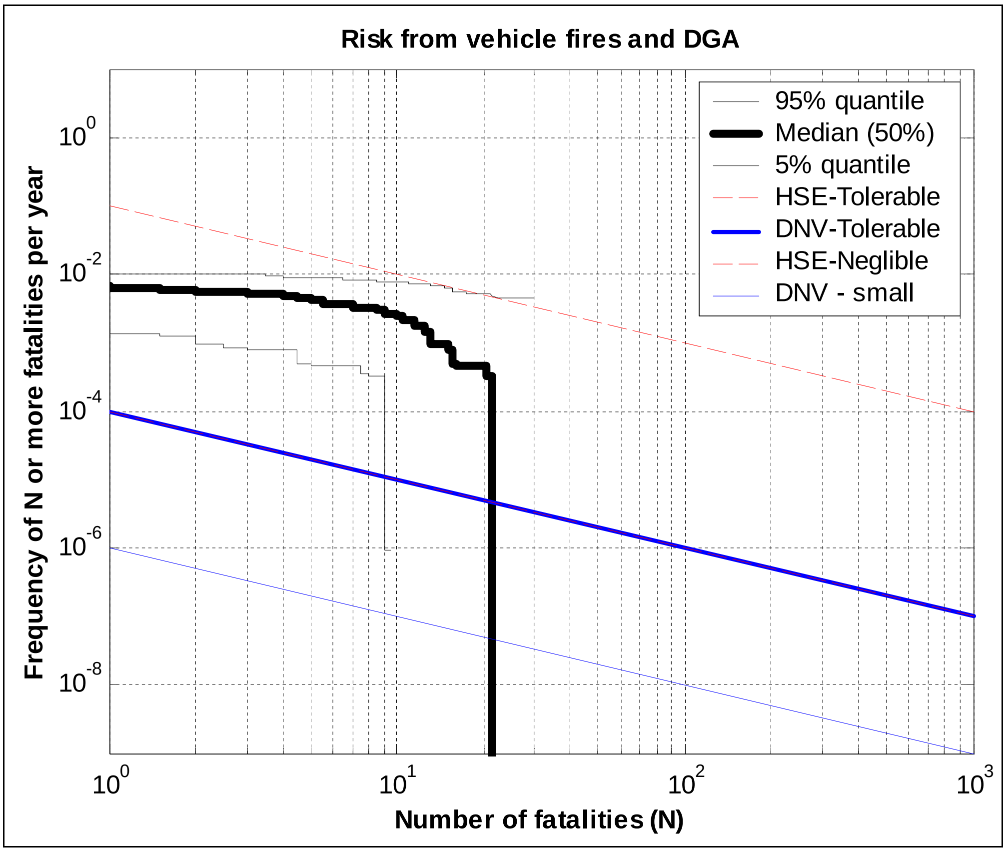


Figure 48. FN curves showing risk compared to limits set by the British Health and Safety Executive (HSE) and DNV.

As Figure 48 shows, risk curve (5-95% quartile) is in the ALARP (As Low As Reasonably Practicable) region of the HSE criteria but far from being even tolerable compared to DNV criteria.

The expected value of all risks was calculated to be according to Table 13.

Table 13. Expected value for statistical fatalities given in yers

	5% quartile	Average	95% quartile
Expected value (all risks)	0.083	0.172	0.407
Expected value (all risks exclusive collision risks)	0.00003	0.073	0.292
Return period (in years, all risks)	12	6	2
Return period (in years, all risks exclusive collision risks)	29157	14	3

As above table reveals clearly then the uncertainty is very large especially for risks other than collisions.

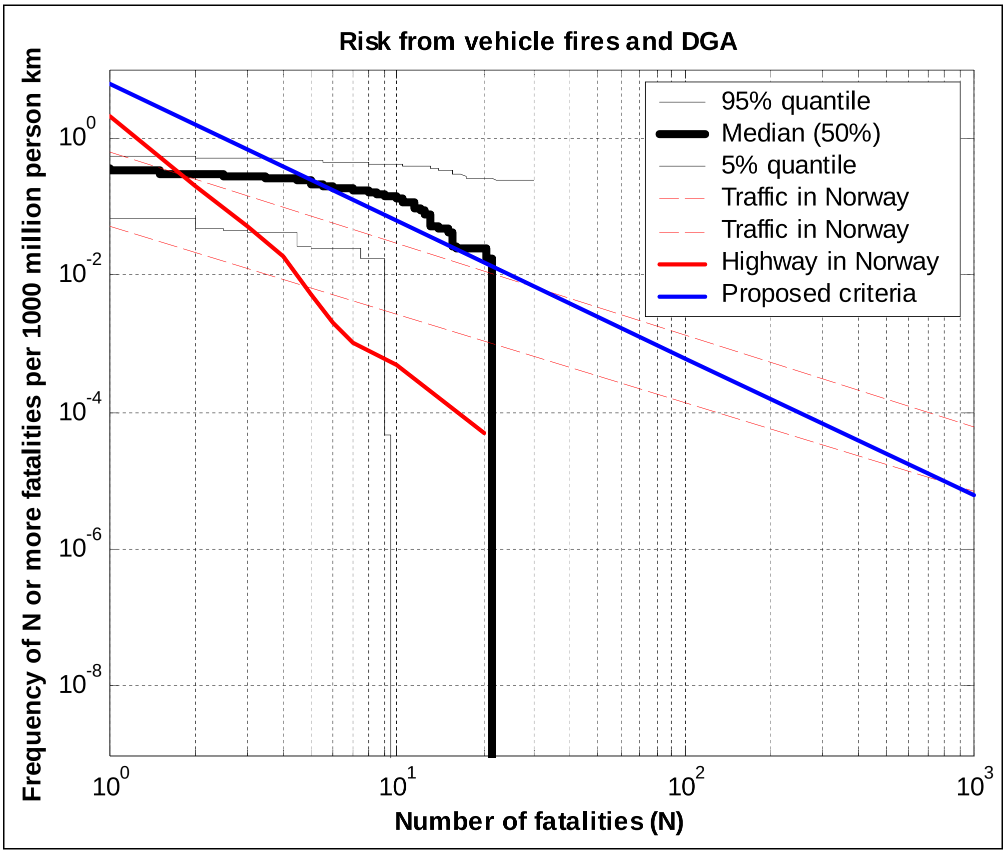


Figure 49. FN curves showing risk compared to limits set by the Norwegian Public Road Administration (Statens Vegvesen).

As Figure 49 shows, the largest part of the risk curve (5-95% quartile) is above the suggested criteria. If slope in the proposed criteria would have been set to –1 then risks in the Hvalfjörður Tunnel would have been close to be regarded as tolerable. Note that risk from collisions are however not included in the FN curve.

5.4 Discussion about risk criteria

Summarizing results from the individual and societal risk then risk can be regarded as tolerable if the tunnel is being regarded as an object but unacceptable if compared in the unit per travelled km. As it lies in the ALARP region then it is at least clear that means should be taken to lower the risk if these can be proven to be reasonably practicable. This could be done by using either Cost benefit or Cost Effective methods.

It is apparent from above that risk can be presented in many ways and the need for standardization is thus obvious. But what units are preferable? Using the criteria which looks at the risk per travelled kilometre can be interpreted as a road standard. All roads should therefore live up to this standard regardless of how many use it or how long it is. Applying this vision to all roads would without doubt lead to wastage of money because a road segment can be very dangerous (per km) without posing any substantial threat to the society due to little traffic or little length.

Looking at the risk as yearly frequency is therefore perhaps more attractive. There is however one imperfection in using this criteria, namely if this criteria would be applied to all "objects" in the road system (Tunnels, Bridges, etc.) what would that lead to. Apparently would that lead to having many structures in the road system which are riskier than other ordinary roads. More frequent accident in these structures than other will assumingly lead to increased pressure on authorities to improve safety in these structures. Improving safety in a structure like a tunnel might however cost enormous amounts of money. It is reasonable to assume that safety measures done afterwards are more expensive then safety measurement planned before a structure is being built. It is also likely that in the future, standards for road safety will get higher and comparing the tunnel to the old road will not be justifiable because many users would never have crossed the fjord if the tunnel didn't exist.

As stated earlier, decreasing risk below some criteria can lead to wastage of money. Using a hybrid of FN curves and Cost Benefit or Cost Effective analysis for future structures seems to be the most appealing choice. The QRA/PRA models can serve as useful tools to estimate effects from various improvements.

People perceptions of driving through tunnels needs to be explored because there are reasons to believe that people perceive the risk of driving through the tunnel both as unknown and dreadful (in the upper right corner in Figure 7) or in the same class as nuclear power for example. If this theory proves to be right then tunnels should be even safer than roads in order for people to accept the risk of using them.

Today the tunnel is used frequently but one severe accident might change people's perception so greatly that authorities and tunnel owners would have to improve safety immediately with all its extra cost. Doing things right from the beginning is perhaps an appropriate phrase in this context because improvements on structures like these can be very costly.

6 RISK REDUCTION/CONTROL

Results from Chapter 5 indicate strongly that means to lower the risk further should be closely analysed.

Risk can be decreased objectively in two ways by:

- Reducing frequency of accidents and by
- reducing consequences from those accidents.

Subjectively, the way people perceive the risk can be affected positively. This is perhaps as important as decreasing the risk objectively because the way people perceive risk is reflected strongly by authorities. To exemplify this one might consider how much money are being spent today to prevent terrorism knowing that in the year of 2001, 42,196 persons were killed in traffic in USA alone! NHTSA (2003).

6.1 Ideas to reduce risk – suggested working procedure

As this project has moved forward, a number of ideas have crossed by which might reduce the risk. These ideas have not been evaluated at all but should be evaluated in the near future. Using the model developed in this thesis might be helpful in measuring effects from these ideas.

<u>Ideas to reduce consequences:</u>

1. Shorten the response time for fire brigade to arrive by placing it near the tunnel.
2. As the wind velocity in a tunnel is increased, the less toxic and less hot will the smoke will be. Evaluation of different ventilation tactics should be considered and incorporated into the response plan.
3. Maintain a fixed velocity of wind in North-South direction so the fire brigade from Akranes can enter the tunnel in a smoke free zone and put fires out quickly.
4. Install sprinkler heads.
5. Install One Seven fire extinguishing equipment.
6. Install a water wall to one side of the tunnel as an alternative escape route.
7. Install TV monitoring throughout the tunnel.
8. Install a hot wire into the middle of the road so a rescue vehicle (preferably battery driven) with a heat detection camera can drive into the tunnel through thick smoke and rescue people.
9. Install detector cables with thermocouples to monitor temperature.

10. Install internal warning signs to warn vehicles driving against the smoke to stop and turn around before they get caught in the smoke.
11. New tunnel beside the old one should be considered thus creating a unidirectional tunnel in each direction. Ventilations should be designed so that the smoke will always travel in the same direction as the traffic so vehicles approaching the fire can be free from smoke at all times.
12. Update response plan regularly and test and train parts of it regularly (at least yearly).
13. Inform the public of what they should do in case of a fire in Hvalfjörður Tunnel.
14. When announcements of accidents are broadcasted in the tunnels, the message should be very clear on what has happened and what people are supposed to do. In case of a fire, everyone should be ordered to get out of the tunnel immediately, leave their vehicles behind and get a lift from someone else if that’s the only way to get out.
15. Check regularly if larger vehicles have a fire extinguisher onboard and check if drivers have knowledge of how they should be used.
16. Evaluate different transport limitations for vehicles carrying dangerous cargos or those who pose a special threat.
17. Install a water pipe inside the tunnel which fire services can connect their fire hoses to.

Ideas to reduce the likelihood for a hazardous event occuring:

1. Check if motors in heavy vehicles are being hot.
2. A sign should remind drivers to check their engine temperature while driving through the tunnels and drivers of heavy vehicles should be reminded to drive slowly down in order to avoid overheating brakes. Use of lay-bays should be encouraged in this context.
3. Distinguish in a clearer manner between opposite lanes or even install a physical barrier. Middle line could for example be double (0.5 m apart) to clearly distinguish between lanes.
4. Overtake on an opposite lane should be clearly banned everywhere in the tunnel.
5. Implement a safety management system.
6. Inform the public on how they should behave inside the tunnel.

The purpose of solving problems in many steps where all ideas are first gathered before any evaluation of them takes place is to avoid excluding ideas which might at first sight be rejected but accepted after closer evaluation. The credibility of decisions will be much better because they have been made by looking into a variety of choices instead of perhaps 2 or 3. This solution process was for example used to come up with new ideas to reduce traffic accidents in Sweden, Mattson (2000). The above list can therefore be seen as the first step of finding ways to reduce the risk.

As the number of ideas can be great, the next step needed would be to do a preliminary analysis in order to choose, perhaps, 4 or 5 ideas, depending on the resources available for this task, which then would be evaluated closer. This closer evaluation would consist of estimation on effects from each idea (saved lives) and calculation of cost.

Having information about cost and effect from each idea makes it possible to rank them in order of most attractive to least attractive. If this reveals that some of the options are very attractive, especially if compared to other improvements in the road systems they should be implemented. But if these are associated with any question marks a cost – benefit analysis should be performed. Vegagerðin (the Public Road Administration) uses cost benefit analysis frequently in their road constructions so they should be able to provide all necessary data to perform a thorough Cost Benefit analysis. A simple benchmark is to consider how much money people are willing to pay to save one human live. A measurement which might save many lives or even exclude the possibility of catastrophe involves huge benefits which should be weighted against its cost.

6.2 Control

Controlling risk in Hvalfjörður Tunnel should be done proactively. Tunnel owner and appropriate authorities should constantly monitor current status. This means that answers to the following key questions should always be available[1].

- Is the risk increasing or not?
    - Are ways to lower the risk within reasonable limits constantly under consideration?
- Is the response plan working?
    - Is the response plan prepared to handle the worst case scenario including how things should be handled in the aftermath?
    - Are all acting members prepared?
    - Is it being rehearsed on regularly basis?
    - Is it being revised on regularly basis?
    - Are tunnel operators being trained and educated to work according to the response plan in an emergency situation?
    - Are summer employees getting appropriate training and education?
- How does the public perceive the tunnel safety?
    - Are they concerned about using the tunnel?
    - How would a catastrophe affect the traffic through the tunnel?
    - Does the public feel that everything which can be done is actually being done?

To answer these and other questions, regarding the risk management in the tunnel, a system to manage these questions is highly recommended. The health, safety and environment management system described in Kemikontoret (1996) might be used as a starting point to develop a management system for the tunnel. This management system should be developed with participation of all working staff of Hvalfjörður Tunnel to ensure their involvement and enthusiasm. To implement successfully a management system, support from the management board and the

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[1] The mentioned points do not reflect in any way how things are currently being managed.

executive director is very important. Without their full support, management systems are doomed to fail.

7 CONCLUDING REMARKS AND RECOMMENDATIONS

7.1 General discussion

7.1.1 Method

The method used to quantify risk in Hvalfjörður Tunnel was successful in terms of expressing risk in an objective way as thoroughly as possible (meaning FN-curve with confidence limits). Performing this type of analysis is however quite complicated and time consuming because it involves handling enormous amount of data which increases also the risk for calculation errors. The main advantage of this method is however that it reveals almost all possible outcomes. By saying “almost“ instead of “all” is because even though efforts to incorporate all uncertainty have been made, one can never be sure that all uncertainties have been incorporated. Variables were for example not correlated to each other in the Monte Carlo Analysis, but some of them perhaps should have. It is for example likely that a high initial wind velocity might cause a more severe fire.

Using single values instead of distributions is like looking at an object from only a single angle instead of all possible angles thus revealing the object thoroughly. Doing a thorough analysis like this should thus be regarded as strength because the risk has been analysed to a very deep level.

7.1.2 Results

The individual risk of driving through the tunnel is not acceptable if compared to the historic level of fatalities per driven km both in Iceland and Norway. But as a single object and if compared to the other option that drivers have it can be concluded that the tunnel is the best available option. Evidently, the risk should be lowered but difficulties arise when considering to what extent the risk should be lowered. Should it be lowered until the risk is less then one of the criteria presented? As Mattson (2000) points out, lowering individual or societal risk to a certain given level can easily lead to a situation where available resources (money) in society are not being effectively spent. Spending for example 100 million Icelandic kronur on some safety measure in Hvalfjörður Tunnel might perhaps save one life over a 30 year period while the same amount of money spent on other traffic safety measures like bridges, might safe 20 lives over the same period. The willingness of people to avoid catastrophes should however not be underestimated.

Proactive risk management for Hvalfjörður Tunnel is therefore of high importance as a catastrophe in the tunnel would be considered as a huge failure unless it could be proved that every reasonable means had been taken to lower the risk. In other words owner and appropriate authorities should prepare themselves to tackle a catastrophe in order to minimize side effects.

Risk of social hazards like sabotage and terrorism are hazards which need to be evaluated at all times. Road tunnels are generally vulnerable structures which can easily be used to cause tremendous consequences. How to avoid such acts is not an easy task but means to reduce the likelihood of such events should be a part of the tunnel response plan.

7.2 Conclusions and recommendations on further work

Concluding remarks and recommendations from this project can be summarized in the following points:

- Risks in Hvalfjörður Tunnel are clearly on the edge of being acceptable
- Actions to lower the risk should be taken by using CBA and/or CEA.
- Calculating benefits from safety measures should account for saved lives.
- Crossing the fjord by using the tunnel is roughly 6 times safer than using Hvalfjörður Road which means that the tunnel is the best available option.
- Risk is judged tolerable if risk is compared to criteria using the unit per year.
- Risk is unacceptable if the risk is compared to criteria using the unit per travelled km.
- The fact that the risk is on the verge of being acceptable indicates that the standard, which the tunnel was constructed by, is not good enough.
- Estimation on risks in tunnels is very uncertain.
- Results from the VST fire risk assessment is almost equal to the average risk presented in this thesis.
- A thorough risk analysis should be performed before new tunnels are constructed to avoid potentially costly safety measures afterwards which might have been avoided if they had been considered in the design stage.
- Evacuation and rescue tunnel beside the road tunnel should be a standard for all future road tunnels or at least be seriously evaluated. Evacuating a tunnel several km in length by foot will always be critical, regardless of other measurements implemented.
- A policy for road safety in tunnels and other road structures is needed. Should they be equally safe as other road segments or should they be safer or allowed to be less safe?
- Appropriate risk criteria should be constructed following the above mentioned policy.
- Safety management system should be applied in road tunnels.
- What happens when the tunnel is handed over to the state raises many questions marks. There is not doubt that the staff at Spölur plays an important role in the safety systems. Any changes to their role should therefore be evaluated closely.
- Side effects from a catastrophic accident have not been evaluated but they might have serious consequences on the communities relying on the tunnel

in the long term. In short term, a catastrophic accident would probably have a tremendous psychological effect on people in the whole country, similar to the avalanche accidents 1995 in Súðavík and Flateyri where the lifes of 14 and 20 people respectively were lost (Morgunblaðið, 1995 January 18 and Morgunblaðið, 1995 October 29). These tragic accidents are the ones that people just don't want to happen again and people are willing to pay considerable amounts of money to secure that they will not be repeated. Expensive structures, built after the avalanches fell, to stop future avalanches from falling again on these villages, are a living proof of that firm willingness to avoid catastrophes from happening again.

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A MODEL TO QUANTIFY EFFECTS FROM TUNNEL FIRES ON HUMANS

In order to determine the effect from fires in tunnels there are numerous factors that need to be considered:

- The fire, how fast it grows, how big will it become and for how long time.
- Temperature in the smoke layer.
- Radiation from flames.
- Movement of smoke through the tunnel, direction and speed.
- Stratification of the smoke.
- Rate of toxic species produced in the fire.
- Geometry of the tunnel.
- Et cetera

Above factors describe the physical effects from a fire but there are also numerous other factors which account for what effect the fire will have on persons in the tunnel:

- Awareness time.
- Behaviour and response time.
- Movement time.
- Amount of people, exposed to the fire.
- Placement of accident
- Distance between vehicles, thus the distance to the nearest exit
- Et cetera.

In the following chapter these factors and others will be quantified and a model to estimate the fatalities due to a tunnel fire will be proposed. There is also in Appendix D a qualitative description on circumstances that might arise in a fire scenario inside the tunnel and might be helpful in understanding some of above parameters and what difficulties are indeed involved doing an estimation like this.

A.1 Characteristics fire curves

Available fire test data on full scale vehicle fires can be found in the literature but are rather few. Ingason (2004) found few test data which Ingason used to propose design fire for passenger vehicle, busses and trucks. These curves are expressed mathematically according to the following equations:

$$Q(t) = at^2 \qquad 0 \le t_1 \qquad \textbf{Eq. 1}$$

$$Q(t) = at_1^{\ 2} = Q_{\max} \qquad t_1 \le t \le t_2 \qquad \textbf{Eq. 2}$$

$$Q(t) = Q_{\max} e^{-b(t-t_2)} \qquad t \geq t_2 \qquad \textbf{Eq. 3}$$

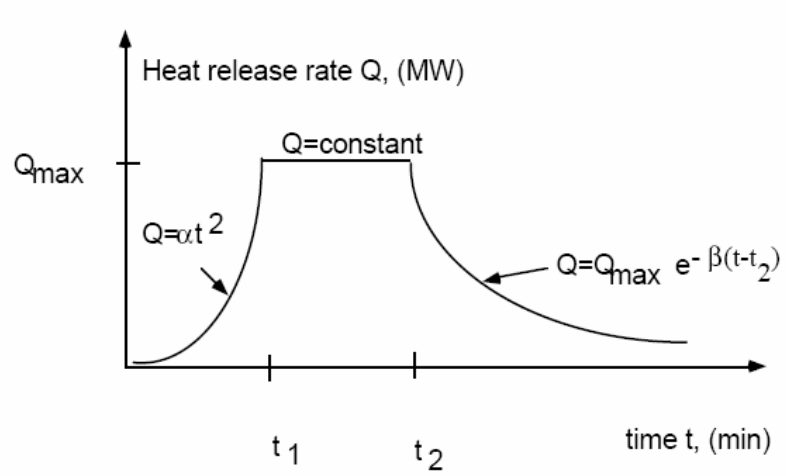

Figure 50. Schematic design fire curve (Ingason, 2004)

And the proposed parameters are shown in table 1.

Table 14. Proposed parameter for design fire (Ingason, 2004)

Type of vehicle	Q_{max} (MW)	α (kW/s^2)	β (1/s)
Passenger vehicle	4	0,01	0,001
Bus	30	0,1	0,0007
Truck[2]	(15-130)	-	-

The above equations will be used to describe possible fire curves for different scenarios in the tunnel. The proposed parameters, see table 1, describe the worst case scenario for each type of vehicle and are therefore perhaps not appropriate to use in a uncertainty analysis as this one, instead appropriate distributions to the variables in the equations that describe the fire curve will be assigned to account for the fact that vehicles burn differently. It is also assumed that the fire brigade will not manage to put fires out as it will take the fire brigade about 15-30 minutes to arrive at the scene and start working and at that time most fires will already have reached a peak heat release rate and it will probably take many minutes for the fire brigade to extinguish the fire, if they can even reach close enough to the fire.

A.2 Average temperature in the smoke

Assuming that the smoke in the tunnel is evenly distributed through the tunnel section then the average temperature, T(x,t) in the smoke at a certain given time

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[2] The fire load for a truck fire varies greatly and therefore no attempt was made to determine Q_{max}, α and β. (Ingason, 2004)

and distance, x, from the fire origin can be calculated with the following equations (Berqqvist, Frantzich, Hasselrot, Ingason, 2001):

$$T_g(x,t) = T_0 + \left[T_{g,0}(t) - T_0\right] e^{-\frac{hP_x}{r_0 u A C_P}} \qquad \textbf{Eq. 4}$$

Where

$$T_{g,0}(t) = T_0 + \frac{0{,}7Q(t)}{c_p r_0 u A} \qquad \textbf{Eq. 5}$$

is the average gas temperature at the fire source (x=0) at the time $t = t - \frac{x}{u}$, that is t is the the time it takes to transport the generated heat at the fire origin to the distance x, T_0 is the initial air temperature in the tunnel, h is the lumped heat transfer coefficient, Ingason (2004) has found out that h varies between 20-40 W/m^{2}K for tunnels, P_x is the tunnel perimeter, here, to simplify calculations, the average perimeter for the whole tunnel was used, r_0 is the air density, 1,2 kg/m3 at 20°C, u is the average wind speed in the tunnel, c_P is the thermal heat capacity for air, 1kJ/(kgK) and A is the tunnel section area, here, to simplify calculation, the average tunnel section area was used.

A.3 Direction and velocity of wind in the tunnel

In the southern part of the tunnel the rock is a few degrees hotter than in the northern part thus creating a natural draught from north to south due to bouyancy effects. Northern winds are also the dominant wind direction in the region. Normally it can thus be assumed that wind will initially be blowing from North to South with a velocity of 1-2 m/s.

If there is no external wind or forced longitudinal ventilation in the tunnel the average cold gas velocity, u, may be estimated by using the following equations (Ingason, 2004),:

$$u = \sqrt{\frac{2g\Delta h\left(1 - \frac{T_0}{\bar{T}}\right)}{\frac{\bar{T}}{T_0} + K_1 + \frac{f_D}{D_h}\left(L + L_s\left(\frac{\bar{T}}{T_0} - 1\right)\right)}} \qquad \textbf{Eq. 6}$$

where

$$\bar{T} = T_0 + \frac{\frac{2}{3}Q}{P_x h L_s} \qquad \textbf{Eq. 7}$$

is the average temperature over the hot smoke stack length, L_s is the stack length, L is the total tunnel length, g = 9,81m/s^2 is the acceleration due to gravity, Dh is the height of the hot smoke stack,

$$D_h = \frac{4A}{P_x}$$ **Eq. 8**

is the hydraulic diameter, f_D is a friction factor dependent on the Reynolds number which varies between 0.015 - 0.03 for most tunnels and K_l is a pressure loss coefficient at the entrance of the tunnel (equal to 0.5 if the entire tunnel is filled with smoke).

If however a fire occurs in the northern slope then it is possible that the smoke will turn the direction of wind around due to buoyancy forces of the smoke. If and when this can happen is particularly important to know because that changes which part of the tunnel will be filled with smoke and therefore the length of the risk zone for persons but also which fire brigade can possibly enter the tunnel (Reykjavik fire brigade enters from south and Akranes brigade from north). To get some understanding about this possible behaviour it was decided to investigate different sizes of fires in the middle of the northern slope by using CFD code. The code used for the simulations was FDS (version 3) from NIST (National Institute of Standards and Technology). A thorough description of circumstances used in the simulations can be found in Appendix F. Results from these simulations indicated that if a fire is larger than 3 MW then the wind will change its direction relatively quickly. These results can however be questioned due to the complexity of this phenomenon and many uncertainties in the simulation process. One thing is however certain; smoke will start to flow upwards at some point and as the fire gets larger thus more likely it is that the smoke will overcome the natural N-S wind draught. When exactly this will happen is based on many factors, initial wind in the the tunnel, direction and magnitude of wind outside the tunnel, growth rate of the fire, placement of fire, amount of vehicles in the tunnel et cetera. It is theoretically possible to simulate all these different circumstances in FDS in order to get a more precise answer, but practically almost impossible because of the time each simulation in FDS takes (about 12 hours with a Pentium II, 700 MHZ Processor). A rough assumption based on these few FDS calculations was therefore done, that is if the maximum heat release rate is larger than 3 MW then the smoke will always flow upwards, regardless of the initial wind flow.

For all fire scenarios, apart from the Petrol Tank fire, the average velocity of wind in the tunnel was estimated by using both the CFD calculation and by using equation 6. For the Petrol tank fire scenarios the velocity of wind was estimated using only equation 6 due to the fact that Petrol fires reach their maximum heat release rate very quickly so the steady state can be expected to be reached quickly and equation 6 thus valid very quickly.

A.4 Determination of gas concentration in the smoke

To determine the average gas concentration, $X_{i,avg}$, of CO (Carbon Monoxide), HCN (Hydrogen Cyanide) and CO_2 (Carbon dioxide) at a certain position downstream from the fire the following general equation was used (Ingason, 2004):

$$X_{i,avg} = Y_i \frac{M_a}{M_i} \frac{Q(t)}{\dot{m}_a H_c} \tag{Eq. 9}$$

Where i is the name of the species, Y_i is the mass yield for chemical i (kg released of the chemical i for each burnt kg) for well ventilated fires, M_a is the mole mass of air (28,95g/mol) and $\dot{m}_a$ is the mass flow rate of combustion gases. Ingason (2004) has collected yields and heat of combustion for various materials, see table 2 which might represent materials found in vehicle.

Table 15. Yields and chemical heat of combustion for well ventilated fires (Ingason, 2004)

Type of material	Y_{CO2}	Y_{CO}	Y_{HCN}	H_c
	kg/kg			MJ/kg
Wood	1,27	0,004		12,4
Rigid Polyurethane foam	1,5	0,027	0,01	16,4
Polystyrene	2,33	0,06		27
Mineral oil	2,37	0,041		31,7
Average	**1,87**	**0,033**	**0,01**	**21,9**

To determine the average cross section mole fraction of oxygen in the combustion gases at a certain position x from the fire the following equation was used:

$$X_{O_2,avg} = 0{,}2095 - \frac{M_a}{M_{02}} \frac{Q(t)}{\dot{m}_a 13000} \tag{Eq. 10}$$

To determine the average cross section visibility in the smoke at a distance x from the fire source the following equation (Berqqvist, et. al, 2001) was used:

$$V = 0{,}87 \frac{uAH_c}{Q(t) D_{mass}} \tag{Eq. 11}$$

Where D_{mass} is the optical density for the fire load.

A.5 Factors leading to incapacitation and/or death

Causes of fatalities in fires are mostly related to inhalation of toxic gas concentrations and exposure to heat and radiation from flames. In UK, for example, it has been estimated that nearly half of all fatalities in fires are due to inhalation of toxic smoke (Purser, 1988) and the other half due to heat and burns. In USA there is evidence that roughly ¾ of fire victims die due to smoke inhalation. Autopsy results of those fire victims showed that the vast majority had sufficient levels of carboxyhemoglobin in their bloodstream to cause incapacitation or death. Many researchers have therefore concluded that Carbon Monoxide is the dominant toxicant present in fire gases (Pitts, 2001).

Most narcotic gases produce their effects by causing brain tissue hypoxia. Victims are often not aware of intoxication and can maintain full body function until a certain dose of narcotic is reached. If exposure continues, weakening of normal function is rapid and intensive, beginning with signs similar to effects from severe alcohol intoxication consisting of drowsiness (lethargy) or enjoyment (euphoria) with poor physical coordination followed by rapid unconsciousness and death if exposure continues.

In order to predict when a person has little or no chance of survival it was decided to use the concept of Fractional Effective Dose (FED). This concept is based on that once a person has been exposed to certain dose, in this case amount of heat or a certain concentration of toxic smoke, for a certain given time then the person will either incapacitate or die, see equation 12.

$$FED = \frac{dose\ received\ at\ time\ t}{effective\ dose\ needed\ to\ cause\ incapacitation\ or\ death} \quad \textbf{Eq. 12}$$

In real fires the dose changes often dramatically over time and because effects from most toxicants increases exponentially with increased concentration it is necessary to sum up fractions for each small period of time until the FED reaches unity (FED=1.0) which means that a person is predicted to incapacitate, (loose his conscious). In this analysis, it is however assumed that FED=1.0 equals death of a person. This is based on the fact that a person which incapacitates in a fire will be further exposed while the fire is still burning. Even though a person is not being exposed further to fire and receives necessary medical care immediately, fire victims are known to die hours or even days later due to their wounds. As one can imagine it is also a very tough task for a fireman to enter a smoke filled tunnel, several km in length, in order to rescue trapped people and then perhaps carry them out by hand. By considering these facts it is obvious that once an incapacitation in a tunnel has occurred, chances of survival are small.

Results from chemical studies of a large- and small-scale experimental fires and animal exposure to the decomposition of products for a wide range of materials have revealed the following important points (Purser, 1998):

- The amount of toxic products in the smoke depends considerably upon different conditions of temperature and oxygen supply they are decomposed at.
- For similar conditions, but different decomposing materials, similar amounts of toxic chemicals are however produced.
- The toxicity of smoke is dominated either by a narcotic gas (CO or HCN) or irritants.
- Interaction between different narcotic gases or, between narcotics and irritants were found to be approximately additive so effects from different toxic components can be summed up.

There is generally little information available how much of toxic products are produced for a burning passenger vehicle. In Piarc (1999) there is table showing CO_2 and CO production for a few types of vehicles, these values are however related to kg of CO or CO2 produced per second in the corresponding fire, not kg produced per kg burned as yields are usually given and the gas concentration formulae above are based on.

In the following chapter each contributing factor to fatality, used in this analysis, will be discussed briefly.

A.5.1 Carbon Monoxide

When a person inhales Carbon Monoxide it enters the bloodstream and combines with the hemoglobin in the blood to form (COHb), which reduces the amount of oxygen supplied to the tissues of the body, particularly the brain tissue. Loss of consciousness is predicted at 40% COHb but can occur at lower levels (~ 30% COHb) and is dangerous for subjects with compromised cardiac functions. Death is predicted at 50 to 70% COHb (Purser, 1998).

Purser (1998) derived an equation for the fractional effective dose to incapacitation as follows:

$$F_{Ico} = \frac{3{,}317 \cdot 10^{-5} RMV\left(ppmCO\right)^{1{,}036} t}{D} \qquad \textbf{Eq. 13}$$

Where

*RMV = 25 l/min (*light activity, walking at 6,5km/h) is the volume of air breathed. 25l/min was thought as a representative value for people evacuating Hvalfjörður Tunnel. *t* is the exposure time in minutes. *CO* is the concentration of CO in ppm. *D* is the corresponding COHb concentration in blood when incapacitation occurs in percents (30% for light activity).

When concentration of CO is changing over time the time to incapacitation can be estimated by summing up the multiplication of each time step *Dt* with the corresponding concentration, see equation 14, until F_{ICO} reaches unity (value of 1).

$$F_{Ico} = \sum \frac{3{,}317 \cdot 10^{-5} RMV\left(ppmCO\right)^{1{,}036} \Delta t}{D} \qquad \textbf{Eq. 14}$$

A.5.2 Hydrogen Cyanide

Hydrogen Cyanide is always present when materials containing nitrogen are involved in fires. Nitrogen is found in materials like acrylics, polyurethane foams, melamine, nylon and wool. It is very likely that nitrogen based materials will be present in vehicle fires.

Hydrogen Cyanide concentrations under 80 ppm will only have a minor effects over a period up to 1 hour but from 80 to 180 ppm the time to incapacitation varies from 30 to approximately 2 minutes respectively. High concentrations of HCN are thus only needed for few minutes to cause incapacitation and consequently to death later from perhaps other factors like accumulation of CO. In Purser (1998) the following equation describing the fractional effective dose to incapacitation can be found:

$$F_{Icn} = \frac{t}{e^{5.396-0.023 \cdot ppmHCN}} \qquad \textbf{Eq. 15}$$

$$F_{Icn} = \sum \frac{\Delta t}{e^{5.396-0.023 \cdot ppmHCN}} \qquad \textbf{Eq. 16}$$

Here equation 15 is used if concentration of HCN is steady over the time period, t, but equation 16 for a changing concentration of HCN. As can be seen from equation 15 and 16, even if there is no hydrogen cyanide present it is still possible to die from Hydrogen Cyanide intoxication! To exclude this possibility a threshold limit of 40 ppm was used in the calculation. As stated above, 80 ppm has only a minor effect so a threshold limit of 40 ppm should be a conservative selection.

A.5.3 Hypoxia

A concentration of oxygen, at approximately 10 percent, can cause hypoxia with similar effects as intoxication of CO and HCN have. In Purser (1998) the following equation describing the fractional effective dose to incapacitation can be found:

$$F_{Io} = \frac{t}{e^{8.13-0.54(20.9-\%O_2)}} \qquad \textbf{Eq. 17}$$

If the concentration is changing over time the following equation can be derived:

$$F_{Io} = \sum \frac{\Delta t}{e^{8.13-0.54(20.9-\%O_2)}} \qquad \textbf{Eq. 18}$$

A.5.4 Carbon Dioxide

Carbon dioxide is like Carbon Monoxide always present in fires to some extent. Even though Carbon dioxide itself is not toxic up to a concentration of 5% it stimulates breathing in such way that it the volume of air breathed per minute doubles at 3% CO_2 level and triples at 5% CO_2 level. This increased breathing increases greatly the inhalation of other toxics found in air, like CO and HCN and reduces therefore the time to incapacitation. A multiplication factor, VCO_2, to account for these effects has therefore been derived (Purser, 1998).

$$VCO_2 = \frac{e^{0.1903 \cdot \%CO_2 + 2.0004}}{7{,}1} \qquad \textbf{Eq. 19}$$

Provided that the Carbon Dioxide concentration is stable or increasing then the following equation, based on the fractional effective dose to incapacitation, can be used to estimate the time it takes to incapacitate due to inhalation of CO_2 alone:

$$F_{Ico_2} = \frac{t}{e^{6.1623 - 0.5189 \cdot \%CO_2}} \qquad \textbf{Eq. 20}$$

If the concentration is changing over time the following equation can be derived:

$$F_{Ico_2} = \sum \frac{\Delta t}{e^{6.1623 - 0.5189 \cdot \%CO_2}} \qquad \textbf{Eq. 21}$$

According to equation 20 and 21 then the time to incapacitation starts decrease immediately, even at 0% CO_2. This can of course not be true so therefore it was decided to include only fractions where the concentrations were above normal, which is 0.033% CO_2.

A.5.5 Fractional effective dose of all narcotic gases

The combined effects of all narcotic gases have been estimated with following equation (Purser, 1998):

$$F_{IN} = \left[\left(F_{Ico} + F_{Icn}\right) VCO_2 + F_{Io}\right] \text{or } F_{Ico_2} \qquad \textbf{Eq. 22}$$

This equation is based on 4 assumptions:

1. CO and HCN are directly additive
2. CO_2 increases the rate of uptake of CO and HCN in proportion to its effect on the RMV (volume air/min)
3. The narcotic effect of low oxygen hypoxia is considered to be directly additive to the combined effects of CO and HCN.
4. The narcotic effects of CO_2 are considered to act independently of the effect of the other gases.

A.5.6 Radiation

Evacuating persons should not be exposed to more than 10 kW/m^2 radiation for a few seconds if they are to survive (Purser (1998). This radiation level is therefore used here as the critical radiation level.

In a longitudinal ventilated tunnel, flames that hit the ceiling will stretch out near the ceiling downstream from the fire origin. The horizontal flame length can be estimated with following equation (Berqqvist et. al., 2001):

$$L_f = 1.64 Q^{0.7} \qquad \textbf{Eq. 23}$$

Here Q is in MW and length of flames in meters. The flame length is defined as the length of a 600°C isosurface. By using simple formulae to calculate radiation from hot surfaces, the radiation from the flames to the floor at the edge of the flame was found to be in excess of 10 kW/m^2. The flame length can therefore be used to estimate the critical zone of radiation.

In most cases it is reasonable to assume that the evacuation process from this zone will be completed before critical radiation is attained because most fires don't grow fast enough. It is also reasonable to assume that strong heat from radiation will be such threat to people that they will decide to evacuate almost immediately instead of perhaps trying to put out the fire. Only in cases where the fire growth is very fast, similar to gasoline pool fires, account for the radiation was considered. If fatality is expected amongst people with an initial placement further away from the fire origin than the flames will stretch then it's not relevant to calculate amount of people who will have died due to radiation because they will also have died from other causes.

A.5.7 Heat

There are generally three ways in which exposure of subjects to heat lead to incapacitation or death:

1. Heat stroke (hyperthermia).
2. Body surface burns.
3. Respiratory tract burns.

The rate of heat transfer (heat flux) from the environment to victims occur through convection, conduction and radiation and magnitude of those depends mainly on air temperature, air humidity, velocity of surrounding air, protective value of clothing and the level of activity of the victims (excess of heat generated inside the victim).

Heat stroke happens when the core temperature of the body increases from the normal 37°C to above 40°C. At 40°C core temperature consciousness becomes blurred and the subject becomes very ill. Core temperatures above 42.5°C are fatal unless treated within minutes.

Surface burns occur when the skin temperature, at a depth of 0.1mm, reaches 44,8°C. Burns occur due to heat flux by conduction, convection and radiation. The relationship between time and effect is exponential. For example, the conduction from heated metal at 60°C will result in pain after 1 second and a burn after 10 seconds but at 80°C it will result in pain after 0.2 second and a burn after 1 second. Pain and burns are very likely for air temperatures above 120°C. The immediate pain and the accompanying psychological shock and fear from burning may result in incapacitation during or after fire. Loss of body fluids into the burn results in circulatory failure and a fall in blood pressure which also may lead to collapse and even loss of consciousness. Generally, victims that have burns on 35% of their body surface area have low chances of survival even though it is known that victims with burns up to 80% of their body surface area have survived.

Respiratory damage is greatly dependent on the humidity in the air. Dry air has a very low thermal capacity while humid air has very high. Dry air at 100°C will thus not induce damage below the top of trachea while steam at 100°C will induce severe damage to the entire respiratory tract down to the deep lung and skin burns in the face. Damage to the respiratory occurs therefore never without burns in the skin of the face so it can be assumed that if a person manages to evacuate without serious skin burns that person will not have respiratory damage.

A formula to predict time to incapacitation due to convection of heat with average air humidity has been derived for unprotected persons at rest and 0.5 m/s air velocity as follows (Purser, 1988):

$$F_{Ih} = \frac{t}{e^{5.1849-0.0273T}} \quad \text{for T>37°C} \qquad \textbf{Eq. 24}$$

When temperature in the surroundings is below 37°C then F_{Ih} is equal to zero because heat is then actually being transported from the body. For victims exposed to changing temperatures F_{ih} is calculated with the following equation:

$$F_{Ih} = \sum \frac{\Delta t}{e^{5.1849-0.0273T}} \qquad \textbf{Eq. 25}$$

In reality it can be assumed that, apart from the head, persons evacuating Hvalfjörður tunnel will be wearing clothes with some protective value (instead of unprotected), air velocity is expected to be a little higher (at least 1,5 m/s instead of 0,5 m/s) and people will be moving (instead of at rest). Clothes may in some cases even reduce the tolerance time, especially for temperatures below 120°C, by holding back the heat loss due to evaporating cooling from the body. This difference might have some effect on the time it takes a person to incapacitate but the difference is not expected to be so big that it will affect the overall result dramatically.

According to equation 26 then incapacitation is expected after 26 minutes for a person in a 70°C hot environment. Ondrus (1990) however estimates this time to be 60 minutes. This indicates perhaps that by using Pursers model an overestimation on fatalities due to heat can be expected.

A.6 The evacuation process

The evacuation process from buildings, where there are initially a certain amount of people, is often simplified by describing it as a process consisting of three phases (Frantzich, 1994):

- Awareness time, t_a.
- Behaviour and response time, T_b.
- Movement time, t_m.

The evacuation time is then found by estimating the time in each phase and summing them up as follows:

$$t_e = t_a + t_b + t_m \qquad \textbf{Eq. 26}$$

A thorough description of these parameters can be found in the literature, for example Frantzich (1994) but in the following, the meaning of these terms will be described briefly and a discussion presented on which values for these parameters could be appropriate for Hvalfjörður Tunnel.

A person becomes ***aware*** once he or she receives signals of a situation that might become dangerous. These signals might be smoke spread, the fire itself, fire alarm, message through radio, cell phone, or message from other people.

Behaviour and response time is strongly dependent on the way a person becomes aware of the situation. Signals like heat, smoke, flames or spoken message from persons with authority lead to shorter behaviour and response time while weak signals like an alarm bell leads to longer time. Before people make any actions they often try to seek for more information by for example looking at how other people react to the situation, discuss with other et cetera. Actions in this context might involve trying to put the fire out or evacuate.

To estimate behaviour and response time there has been published proposed values for different types of buildings, depending on circumstances. times given in Table 16, which describes the behaviour and response time for people in their residence, was thought as appropriate to use for road tunnels like Hvalfjörður Tunnel. The only exits are where vehicles enter and exit the tunnel and assuming that most users are aware of where the exits are and most of them are frequent users, it is concluded that behaviour response time in residence houses will be similar in tunnels. This assumption is however questionable and further research is needed.

Table 16. Behaviour and response times from Firecam, Proulx and Hadjisophocleous (1998) (as cited in Frantzich, 2001)

Signals of fire by:	**Behaviour and response time, t_b, (seconds)**
Heat, smoke or flames from the fire	50
Warning as the fire brigade arrives	50
Warning given by other persons	100
Warning by spoken audio message	100
Warning from central alarm	250
Warning from local alarm or smoke detector	250

The ***movement time*** is the time it takes to reach safety once a decision on evacuation has been made. This time is calculated from the walking speed and is dependent on many factors like the physical capability of each persons, visibility in the evacuation route, distance to exit et cetera. Jin, 1976 (as cited in Frantzich,

2001) did a large study on walking speed in smoke; results from his studies are shown in figure 4. Figure 4 shows how the walking speed decreases from 1,2 m/s down to 0,4 m/s as the smoke gets denser or more irritant. Jin also found that the visibility multiplied by the smoke density is almost a constant. If kV=2 (general visibility) is used here as a representative value for Hvalfjörður tunnel then for example the optical density may be calculated to be 0,2 for 10m visibility and that results, according to figure 4, in a roughly 1,2 m/s walking speed.

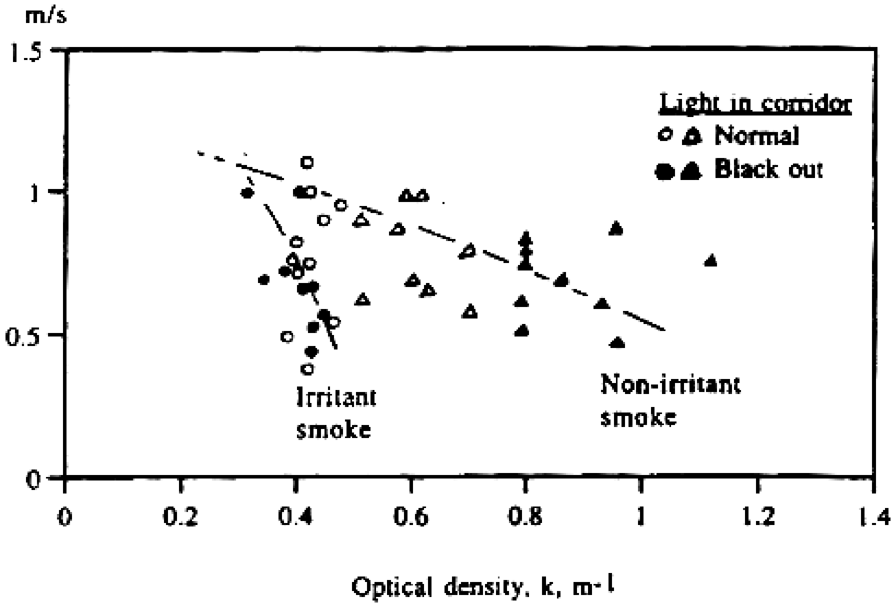

Figure 51. Walking speed in smoke as a function of density and appearance taken from Jin, 1976 (as cited in Frantzich, 2001)

Frantzich (2000) carried out an experimental study for passengers evacuating an underground train in a tunnel. He found out that the walking speed in dense smoke with no emergency lights varied between 0.5 and 1.0 m/s with an average of 0.7 m/s. If however emergency lights were turned on the walking speed varied between 1.0 and 1.8 m/s with an average value of 1.2 m/s. The emergency lights were about 1 m above ground and with a distance of 7.5 m between each light. The study also showed that variation in light strength had little effect on the walking speed, thus it can be concluded that people use lights mostly to localise themselves (distance from wall etc), not to see the environment ahead.

A.6.1 Appropriate values for the evacuation parameters in Hvalfjörður Tunnel

Almost all drivers approaching the fire will probably become ***aware*** of threats as they arrive at the accident scene, face the smoke front or pass evacuating people. Only a few people might become aware of threats through radio because the time it takes for the staff at the toll booth to become aware of the situation and broadcast warning messages is estimated to be in the orders of minutes (typically estimated to be 3-5 minutes) and even then it’s not sure that drivers will hear it because their radios have to be turned on and tuned on the right frequency. Other ways are possible like drivers warning other drivers. In this analysis it is therefore assumed that drivers will only become aware of threats as they arrive at the accident scene or face the smoke front. To simplify calculations the awareness time was estimated to be from 1,5 to 3 minutes from the start of the fire for all scenarios. The awareness time represents therefore in fact the average arrival time at the scene. Exposure to fire was assumed to start after this time had elapsed.

Based on the assumption on how most persons in the tunnel will become aware of a fire in the tunnel, the ***behaviour and response time***, according to table 2, can be estimated to be around 50 seconds. People that arrive late on the scene and meet other drivers that already have decided to evacuate will most likely join them, thus their behaviour and response time will be shorter.

The above simplifications were necessary in order to be able to perform a Monte Carlo simulation but they are expected to only produce a marginal error due to the following reasons:

- The first drivers arriving at the scene will quickly find out that something is wrong but will most likely spend some time finding out what to do, that is evacuate or try to put the fire out.
- The last drivers to arrive at the scene will arrive a few minutes after the fire started but will most likely quickly decide to evacuate as they will probably meet other people that already have decided to evacuate.

In the Tunnel there are luminous lights at ground level which might help people localise themselves in the tunnel so according to findings of Frantzich (2001) the walking speed might be expected to be as high as 1.2 m/s. The walking path in Hvalfjörður Tunnel is however much steeper than Frantzich (2001) used in his study so it will be physically much harder for people to maintain this walking speed. It is also unclear how well the luminous lights will be seen in a dense smoke. A walking speed of 0.7 m/s seems therefore to be a more likely value for the average walking speed. It would be relatively easy to perform an evacuation test in Hvalfjörður Tunnel to reveal a better estimation on this value and should perhaps be performed in the near future.

A.6.2 Calculating the amount of people exposed to fire

In order to calculate the amount of people that might be threatened by a fire, the following facts must be known or estimated.

1. Amount of vehicles entering the tunnel per minute.
2. Average vehicle velocity in the tunnel in order to calculate the amount of vehicles which are in the tunnel at the same time and average length between each vehicle.
3. Average amount of people per vehicle.
4. Proportion of traffic going south or north.
5. Placement of accident.
6. Response time, which is the time that elapses after the accident has occurred until the tunnels are physically closed for further traffic.

Most of these parameters (1-4) are already known (see chapter 3.3) but others have to be estimated. It is assumed that the placement of an accident is a uniform random variable (all placements are equally likely). The response time was estimated by using the experience already gained at the tunnel. According to a staff member working at Spölur (Tryggvason, 2003 September 3), this time depends on how dense the traffic is when an accident occurs. In normal dense traffic their experience is that they get notification very quickly, often within one minute, mostly from other drivers (using their cell phones) or from the emergency call centre, SOS 112. In all accidents, staff is supposed to close the tunnel immediately and that is done by simply pushing one button, about 20-30 seconds later the tunnel gates are closed completely. From this information the response time has been estimated to be about 1 to 5 minutes with an average of 1.5 minute.

If a fire starts in the tunnel, the following assumptions were made:

- Immediately after the fire starts, vehicles will start developing a queue at both sides from the fire.
- All vehicles that are upstream when the fire starts (smoke free area) will however manage to turn their vehicles around and drive safely out.
- A queue downstream from the fire starts to develop in a single row, equally spaced
- Having information about number of passenger in vehicles, amount of people per meter from the fire origin and the total length can be calculated

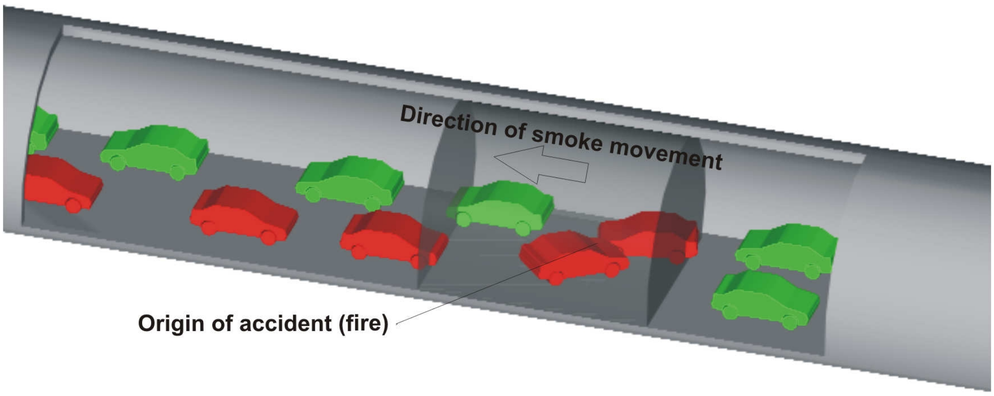

Figure 52. Vehicles in the risk zone (coloured red)

As Figure 52 shows, smoke is moving upwards (to left) and red vehicles are the ones that are assumed to be trapped in smoke. Green vehicles will safely be able to drive out of the tunnel.

The average vehicle length was estimated to be about 3 meters. The distance between vehicles is estimated to be at least one vehicle length. Even longer distance might be expected because the traffic is relatively sparse and drivers queuing up are likely to already have seen the smoke and will therefore be more careful then usually.

The average amount of persons in vehicles was based on information from Haraldsson (2 April, 2003) and are as follows:

- Passenger vehicles: 2.5 persons.
- Trucks: 1.1 persons.
- Busses: 18 persons.

Based on the proportion of passenger vehicles, Trucks and Busses in the traffic the average amount of persons per vehicle was calculated to be approximately 2.56 persons/vehicle.

A.7 Consequences on humans due to fires - overview of the procedure

To estimate the fatality amongst people in the tunnel the calculation procedure can be briefly described in steps, as follows:

1. Description of scenario.
2. Estimate design fire for the scenario, α, Q_{max} and time when decay starts, β.
3. Assume some placement for the fire in the tunnel.
4. Estimate which way smoke will go (north or south) and velocity of the smoke front by using results from FDS and equation 6.
5. Estimate traffic flow into the tunnel (fraction going north and fraction going south).
6. Estimate response time, that is the time that elapses after the accident has occurred until the tunnels are physically closed for further traffic.
7. Calculate amount and total length of vehicles in a single queue downstream from the fire origin.
8. Estimate amount of people per vehicle and calculate amount of people per meter.
9. Calculate effects from fire toxicity, heat and radiation from flames on persons, using equations 4-26, starting their evacuation from different initial position (10, 20, 30 etc. away from the fire origin).
10. Find the deadly zone from 9.
11. If the fire growth is very fast (similar to gasoline fire) then check if the critical radiation zone is longer than the deadly zone found in 10. If it is longer then use this length as the deadly zone.
12. Compare the deadly zone to the queue length and calculate the fatality.

Most of the above factors can be estimated with some certainty but there are however many factors with bigger uncertainties involved. It is for example obvious that the outcome from a certain fire depends greatly on where exactly in the tunnel the fire starts, the density of traffic, distance between vehicles in the queue et cetera. These variables can be described as typical random variables. One could therefore calculate numerous possible outcomes for each single vehicle fire. Under these circumstances designers often determine these values to get the most likely, the most pessimistic, the most optimistic or perhaps probably the worst likely outcome. In this analysis there are many variables involved and many of these can not be estimated accurately. An alternative to these methods is to find which statistical distributions these variables obey and consequently the outcome can also be given as a statistical distribution. Only when the answer is given as a statistical distribution it is possible to see how certain the outcome is. It is possible to calculate the outcome analytically but the simplest way and most forward way to do this is, is to use numerical methods like the Monte Carlo simulation. Risk analyses that have been done for Hvalfjörður Tunnel are all single value analyses and therefore values chosen in these analyses could easily be questioned; what do they represent, worst case, most likely, should they be higher or lower et cetera? It was therefore of a considerable interest to do an analysis that would give almost all possible outcomes.

The Monte Carlo simulation was done using the program @risk, version 3.5 from Palisade Decision Tools.

A.8 Sensitivity analysis for the consequence model

The model is based on many variables and therefore it is important to identify which variables are most sensitive to the final result, hence need the most consideration in the uncertainty analysis. By doing this it is possible to sort out variables that have very little meaning in the final result and therefore more effort can be used to study the important one. This should also be helpful in finding appropriate and effective ways to minimise possible consequences from a fire in the tunnel.

The analyses of sensitivity in variables was performed by choosing a base scenario where all variables were fixed to their most likely value and then variables were varied, one by one. The degree of variation was chosen as the upper or lower limit or in some cases both for each variable. The degree of variation might have been chosen as a fixed value or a percent but that was bound to give wrong result as the variables have a very different degree of uncertainty, one variable might have an upper and lower limit varying by a few percent while another might vary, even hundreds of percent from their most likely value.

The base scenario used was a 2-3 passenger vehicle fire. A further description of how the base values were estimated is summarized in chapter 4.4.1. Table 17 summarizes results from the sensitive analysis.

Table 17. Sensitivity for the 2-3 passenger vehicle fire

Variable	**Value used in the base case**	**Varied value**	**Variation**	**Amount of people downstream from fire**	**Average queue length in the tunnel**	**Length of critical zone**	**Increase/ decrease in critical zone**	**Expected number of deaths**	**Increase/decrease in deaths**
Results for base case				***13,0***	***30,8***	***10,0***		***4,2***	***0,0%***
Placement of accident	1910	2870	50%	15,5	36,7	350,0	3400%	15,5	266,6%
Walking speed	0,7	0,5	-29%	13,0	30,8	240,0	2300%	13,0	207,7%
α	0,01	0,02	100%	13,0	30,8	110,0	1000%	13,0	207,7%
Qmax	8	12	50%	13,0	30,8	90,0	800%	13,0	207,7%
T0	15	20	33%	13,0	30,8	80,0	700%	13,0	207,7%
ΔH	21,9	11	-50%	13,0	30,8	60,0	500%	13,0	207,7%
Awareness time	120	150	25%	13,0	30,8	60	500%	13,0	207,7%
u	1,5	1,1	-27%	13,0	30,8	50,0	400%	13,0	207,7%
Reaction time	50	100	100%	13,0	30,8	40,0	300%	13,0	207,7%
T0	15	10	-33%	13,0	30,8	0,0	-100%	0,0	-100,0%
U	1,5	2	33%	13,0	30,8	0,0	-100%	0,0	-100,0%
Walking speed	0,7	1	43%	13,0	30,8	0,0	-100%	0,0	-100,0%
Average length that one vehicle uses in a quee	6	4	-33%	13,0	20,5	10,0	0%	6,4	50,0%
Average length that one vehicle uses in a quee	6	9	50%	13,0	46,2	10,0	0%	2,8	-33,3%
Average amount of people in one vehicle	2,54	1,7	-33%	8,7	30,8	10,0	0%	2,8	-33,1%
Average amount of people in one vehicle	2,54	3	18%	15,4	30,8	10,0	0%	5,0	18,1%
Traffic	2,54	6,5	156%	33,4	78,8	10,0	0%	4,2	0,0%
Average speed	74,5	50	-33%	15,5	36,5	10,0	0%	4,2	0,0%
Proportion of traffic going South	50	25	-50%	19,5	46,2	10,0	0%	4,2	0,0%
Proportion of traffic going North	50	75	50%	19,5	46,2	10,0	0%	4,2	0,0%
Response time	2,5	5	100%	21,1	49,8	10,0	0%	4,2	0,0%
b	0,001	0,002	100%	13,0	30,8	10,0	0%	4,2	0,0%
DH	21,9	32,8	50%	13,0	30,8	10,0	0%	4,2	0,0%
h	0,03	0,04	33%	13,0	30,8	10,0	0%	4,2	0,0%
YCO	0,033	0,06	82%	13,0	30,8	10,0	0%	4,2	0,0%
YCO2	1,87	2,37	27%	13,0	30,8	10,0	0%	4,2	0,0%
YHCN	0,01	0,02	100%	13,0	30,8	10,0	0%	4,2	0,0%

Table 17 shows clearly how sensitive the model is to different variables. A notice must however be given to the fact that no combined effects are measured here, only single variables are varied one by one. Increase in traffic or response time might therefore, according to table 4, seem to have no effect on the fatality and that is in fact true unless it is combined to changes in other effects that will either increase the critical zone or make the queue more crowded. A different base case with for example higher Q_{max} would almost certainly make some variables less sensitive or vice versa. An extensive analysis, using for example higher Q_{max} might have indicated that more or other factors might be more interesting

Following this relatively simple sensitivity analysis, it became however apparent which variables needed consideration in the uncertainty analysis, which is:

- Placement of accident
- Walking speed
- α - fire growth rate
- Q_{max}- maximum heat release rate
- E- the total energy content in the burning item.
- T_0 - initial temperature in the tunnel
- Reaction time, the time it takes people to decide to evacuate
- Awareness time, the average time it takes for all people trapped to become aware of a fire in the tunnel.
- u, the average velocity of wind in the tunnel
- Average length that a single vehicle uses in a queue
- Traffic, amount of vehicles entering the tunnel per minute
- Response time, the time it takes to close the tunnels physically for further traffic.

Density distributions were assigned bearing in mind that a fire in a certain type of vehicle fire had started and any attempt to put out the fire had failed. Because of lack of information in many cases, distributions were assigned in such way that seemed reasonable to the author. Uncertainties can only be minimised by putting a huge effort into each and every variable but the time frame for a thesis like this does not allow such a deep and thorough study.

B INPUT AND OUTPUT DATA FROM THE SOFTWARE GASOL 2.5 AND RMP

Below is some output data from the software Gasol 2.5 in Swedish.

1 cm hole in a tank in the gaspahse

```
UTDATA FRÅN GASOL

INDATA

LAGRING:
Lagringstemperatur : 15.0 °C
Kondensationstryck : 6.29 bar
Lagringstryck      : 7.00 bar

Gasolen är kondenserad.

UTSLÄPPSTYP      : Hål i tank i gasfasen

Cd-värde         : 0.83

TANKEN:
Form             : cylindrisk
Diameter         : 0.3 m
Längd            : 1.5 m
Fyllnadsgrad     : 80%

HÅLETS STORLEK:
Hålets diameter  : 10 mm
Hålets area      : 0.00008 m²
Utsläppstid      : 717 s

OMGIVNING:
Vägg o dyl. nära : Nej
Uppsamling       : Nej

Utsläppets varaktighet ändras till 716.79 s
eftersom massan i tanken endast är 49.36 kg

VÄDER:
Lufttrycket är 760 mmHg
Temperaturen är 15 °C med en relativ luftfuktighet på 50%
```

Det blåste 1.5 m/s på 2 m's höjd
Natt, mulet.

UTDATA FRÅN JETFLAMMA
Om utsläppet antänds direkt kommer det att resultera i en jetflamma
Jetflammans längd är 4.6 m
Avst. från utsläppspunkten i jetriktningen till:

3:e gradens brännskador	5.6 m
2:a gradens brännskador	5.6 m
1:a första gradens brännskador	6.6 m

Avst. från utsläppspunkten vinkelrätt mot jetriktningen till:

3:e gradens brännskador	2.0 m
2:a gradens brännskador	0.0 m
1:a första gradens brännskador	3.0 m

Spridning
KONTROLL AV INDATA
1: Utsläppshastighet : 0.07 kg/s
2: Utsläpps temperatur : 288.00 K
3: Utgångstryck : 5.83 bar
4: Utsläppsdiameter : 0.010 m
5: Vinkel til horizontellt : 0.00 deg
6: Höjd ovan mark : 0.00 m
7: Andel ånga vid utgången : 1.0000 kg/kg

Beräknade värden

Moment input	5.6 kgm/s2
Enthalpi input	28.2 kJ/s
Specific enthalpi	409.0 kJ/kg
Max. Två-fas flöde	0.07 kg/s
I utgångs planet:	
Densitet	10.716 kg/m3
Tryck	5.8 bar
Hastighet	81.81 m/s
Efter flashing :	
Densitet	2.321 kg/m3
Temperatur	288.0 K
Hastighet	81.81 m/s
Radie	0.011 m
Ång fraktion	1.0000 kg/kg

avstånd	koncentration	höjd	radie	temperatur
0.01	1000000.00	0.00	0.01	288.00
0.03	651585.93	0.01	0.02	288.13
0.05	427325.88	0.01	0.02	288.24
0.07	281880.09	0.02	0.03	288.35
0.11	186922.17	0.02	0.05	288.43
0.17	124593.84	0.03	0.07	288.50

0.25 83514.78 0.05 0.09 288.55
6

SPECIFICERING AV INITIALT PLUME FÖNSTER

1: Gasolflöde : 0.069 kg/s
2: Totalt flöde : 0.566 kg/s
3: Fönsterbredd : 0.2 m
4: Nedströmsläge : 0.25 m
5: Initial plymhastighet : 15.8 m/s
6: Initial plym temperatur : 287.9 K
Koncentration 0.122 kg/kg = 83514 ppm
Densitet 1.277 kg/m3
Molnets höjd 0.15 m
Enthalpi -0.1 kJ/kg
Moment input 9.0 kgm/s2

Sista nedströms position 20.25 m
Molnets bredd 2.3 m
Molnets höjd 0.75 m
Koncentration 0.013 kg/kg = 8473 ppm

INTEGRATION RESULTAT
Molnets volym = 9.5 m^3
Molnet är 17.2 m långt och 1.9 m brett
Det innehåller .2829 kg ren propan

UTDATA FRÅN FLAMFÖRBRÄNNING
Avst. från utsläppspunkten i jetriktningen till:
3:e gradens brännskador 20.1 m
2:a gradens brännskador 20.1 m
1:a första gradens brännskador 20.1 m
Avst. från utsläppspunkten vinkelrätt mot jetriktningen till:
3:e gradens brännskador 5.6 m
2:a gradens brännskador 5.6 m
1:a första gradens brännskador 5.6 m

2 cm hole in a tank in the gaspahse

UTDATA FRÅN GASOL

INDATA

LAGRING:
Lagringstemperatur : 15.0 °C
Kondensationstryck : 6.29 bar
Lagringstryck : 7.00 bar

Gasolen är kondenserad.

UTSLÄPPSTYP : Hål i tank nära vätskeytan

Cd-värde : 0.83

TANKEN:
Form : cylindrisk
Diameter : 0.3 m
Längd : 1.5 m
Fyllnadsgrad : 80%

HÅLETS STORLEK:
Hålets diameter : 20 mm
Hålets area : 0.00031 m²
Utsläppstid : 21 s

OMGIVNING:
Vägg o dyl. nära : Nej
Uppsamling : Nej

Utsläppets varaktighet ändras till 20.55 s
eftersom massan i tanken endast är 49.36 kg

VÄDER:
Lufttrycket är 760 mmHg
Temperaturen är 15 °C med en relativ luftfuktighet på 50%
Det blåste 1.5 m/s på 2 m's höjd
Natt, mulet.

UTDATA FRÅN JETFLAMMA
Om utsläppet antänds direkt kommer det att resultera i en jetflamma
Jetflammans längd är 14.1 m
Avst. från utsläppspunkten i jetriktningen till:

3:e gradens brännskador	18.1 m
2:a gradens brännskador	21.1 m
1:a första gradens brännskador	27.1 m

Avst. från utsläppspunkten vinkelrätt mot jetriktningen till:

3:e gradens brännskador	8.0 m
2:a gradens brännskador	11.0 m
1:a första gradens brännskador	18.0 m

Spridning
KONTROLL AV INDATA
1: Utsläppshastighet : 2.40 kg/s
2: Utsläpps temperatur : 288.00 K
3: Utgångstryck : 5.83 bar
4: Utsläppsdiameter : 0.020 m

```
5: Vinkel til horizontellt         :   0.00 deg
6: Höjd ovan mark                  :   1.00 m
7: Andel ånga vid utgången         : 0.3349 kg/kg

Beräknade värden
Moment input                  598.9 kgm/s2
Enthalpi input              476.6 kJ/s
Specific enthalpi             198.5 kJ/kg
Max. Två-fas flöde               0.13 kg/s
I utgångs planet:
Densitet                    30.874 kg/m3
Tryck                        5.8 bar
Hastighet                   247.59 m/s
Efter flashing :
Densitet                    3.487 kg/m3
Temperatur                     231.0 K
Hastighet                   249.40 m/s
Radie                       0.030 m
Ång fraktion                 0.6644 kg/kg

avstånd   koncentration   höjd   radie    temperatur
0.03     1000000.00      1.00      0.03    231.00
0.05       810184.44      1.00      0.04    223.89
0.08       670605.20      1.00      0.05    218.86
0.11       538720.77      1.00      0.06    214.05
0.17       417977.78      1.00      0.07    209.42
0.25       310432.48      1.00      0.10    215.35
0.37       222137.52      1.00      0.15    231.96
0.55       156469.84      1.00      0.21    246.17
0.80       108953.62      1.00      0.32    257.65
1.18        75340.30      1.00      0.46    266.48
1.74        51974.81      1.00      0.68    272.99
2.55        35939.01      0.99      0.98    277.66
3.73        25027.35      1.19      1.40    280.94
12

SPECIFICERING AV INITIALT PLUME FÖNSTER

1: Gasolflöde                    :      2.401 kg/s
2: Totalt flöde                  :     63.975 kg/s
3: Fönsterbredd                  :        2.8   m
4: Nedströmsläge                 :       3.73   m
5: Initial plymhastighet         :        8.2  m/s
6: Initial plym temperatur       :      280.9   K
Koncentration            0.038 kg/kg =  25027 ppm
Densitet              1.270 kg/m3
Molnets höjd             2.19 m
Enthalpi              -7.2 kJ/kg
Moment input            526.0 kgm/s2
```

Sista nedströms position 5.23 m
Molnets bredd 3.1 m
Molnets höjd 2.12 m
Koncentration 0.036 kg/kg = 24044 ppm

INTEGRATION RESULTAT
Molnets volym = 11.4 m^3
Molnet är 5.0 m långt och 3.1 m brett
Det innehåller 1.5376 kg ren propan

UTDATA FRÅN FLAMFÖRBRÄNNING
Avst. från utsläppspunkten i jetriktningen till:
3:e gradens brännskador 13.2 m
2:a gradens brännskador 14.2 m
1:a första gradens brännskador 15.2 m
Avst. från utsläppspunkten vinkelrätt mot jetriktningen till:
3:e gradens brännskador 6.6 m
2:a gradens brännskador 6.6 m
1:a första gradens brännskador 10.6 m

Tank collapse

UTDATA FRÅN GASOL

INDATA

LAGRING:
Lagringstemperatur : 15.0 °C
Kondensationstryck : 6.29 bar
Lagringstryck : 7.00 bar

Gasolen är kondenserad.

UTSLÄPPSTYP : Totalt tankbrott

TANKEN:
Form : cylindrisk
Diameter : 0.3 m
Längd : 1.5 m
Fyllnadsgrad : 80%

Ingen invallning

TANKDATA:
Tankens vikt tom : 20 kg
Designtryck : 7 bar
Bristningstryck : 2901324 bar

Du bör räkna på detta utsläpp som ett momentant utsläpp dvs totalt tankbrott

VÄDER:
Lufttrycket är 760 mmHg
Temperaturen är 15 °C med en relativ luftfuktighet på 50%
Det blåste 1.5 m/s på 2 m's höjd
Natt, mulet.

Pölbranden är 3.82 m hög.
Den lutar 38.96 grader från lodlinjen pga vinden.
Pölens diameter blir 0.9 m
Avst. till 5.0 kW/m2 i vindriktningen från pölens centrum 7.45 m
Avst. till 2.5 kW/m2 i vindriktningen från pölens centrum 9.45 m
Avst. till 5.0 kW/m2 mot vindriktningen från pölens centrum 4.45 m
Avst. till 2.5 kW/m2 mot vindriktningen från pölens centrum 6.45 m

Spridning
SPECIFICERING AV INITIALT PLUME FÖNSTER

1: Gasolflöde : 0.031 kg/s
2: Totalt flöde : 0.031 kg/s
3: Fönsterbredd : 0.9 m
4: Nedströmsläge : 0.00 m
5: Initial plymhastighet : 1.0 m/s
6: Initial plym temperatur : 231.0 K
Koncentration 1.000 kg/kg = 1000000 ppm
Densitet 2.317 kg/m3
Molnets höjd 0.01 m
Enthalpi -81.2 kJ/kg
Moment input 0.0 kgm/s2

Sista nedströms position 300.00 m
Molnets bredd 32.2 m
Molnets höjd 5.84 m
Koncentration 0.000 kg/kg = 54 ppm

INTEGRATION RESULTAT
Molnets volym = 10.1 m³
Molnet är 15.0 m långt och 7.2 m brett
Det innehåller .542 kg ren propan

UTDATA FRÅN FLAMFÖRBRÄNNING
Avst. från utsläppspunkten i jetriktningen till:
3:e gradens brännskador 35.7 m
2:a gradens brännskador 35.7 m

1:a första gradens brännskador 35.7 m
Avst. från utsläppspunkten vinkelrätt mot jetriktningen till:
3:e gradens brännskador 16.5 m
2:a gradens brännskador 16.5 m
1:a första gradens brännskador 16.5 m

BLEVE
UTDATA FRÅN GASOL

INDATA

LAGRING:
Lagringstemperatur : 15.0 °C
Kondensationstryck : 6.29 bar
Lagringstryck : 7.00 bar

Gasolen är kondenserad.

UTSLÄPPSTYP : Cd=

TANKEN:
Form : cylindrisk
Diameter : 0.3 m
Längd : 1.5 m
Fyllnadsgrad : 80%

TANKDATA:
Tankens vikt tom : 20 kg
Designtryck : 7 bar
Bristningstryck : 2901324 bar

VÄDER:
Lufttrycket är 760 mmHg
Temperaturen är 15 °C med en relativ luftfuktighet på 50%
Det blåste 1.5 m/s på 2 m's höjd
Dag, mulet.

UTDATA FRÅN BLEVE

Utsläppt massa var 49.4 kg
BLEVEN's diameter var 23.01 m
BLEVEN varar i 2.3 s
BLEVEN befinner sig 17.26 m över marken.
Avstånd till 3:e gradens brännskador är 13 m
Avstånd till 2:a gradens brännskador är 22 m
Avstånd till 1:a gradens brännskador är 39 m
Tanken delas i 2 delar.

Dessa flyger 277.4 m
Spridning

Below are results from consequence analysis from the software RMP version 1.06

```
Chemical: Propane
CAS #: 74-98-6
Category: Flammable Gas
Scenario: Worst-case
Quantity Released: 50 kilograms
Release Type: Vapor Cloud Explosion
Estimated Distance to 1 psi overpressure: .04 miles (.06 kilometers)

--------Assumptions About This Scenario---------
Wind Speed: 1.5 meters/second (3.4 miles/hour)
Stability Class: F
Air Temperature: 77 degrees F (25 degrees C)
------------------------------------------------
```

C OVERVIEW OF TUNNEL FIRES

Land	Tunnel	Slope	Urban/Rural	Flow of traffic	Length [km]	Years inquired	Average Annual traffic [million veh/year]	Total Traffic Work in million vehicles km	Cases of fire					
									Passenger vehicles		Lorries		All vehicles	
									Number of fires	Rate per 100 million vehicles km	Number of fires	Rate per 100 million vehicles km	Number of fires	Rate per 100 million vehicles km
Austria	Perjen		Rural	Bidirectional	2.9	1987-1991	3	43.5	0	0	0	0	0	0
Austria	Amberg		Rural	Bidirectional	3	1987-1991	5.4	81	0	0	0	0	0	0
Austria	Arlberg*		Rural	Bidirectional	14	1987-1991	1.7	119	-	-	-	-	-	2.5
Austria	Pfänder		Rural	Bidirectional	6.72	1985-88	3.6	96.768	-	-	-	-	-	0.7
Austria	Katschberg*		Rural	Bidirectional	5.4	1987-1991	3.9	105.3	0	0	0	0	0	0
Austria	Tauern*		Rural	Bidirectional	6.4	1987-1991	4.5	144	0	0	0	0	0	0
Norway	Fløyfjell	1%	urban	Unidirectional	3.45	1988-95	9.9	273.24	-	-	-	-	-	1
Norway	Oslo	4-7%	urban	Unidirectional	1.8	1990-95	20	216	-	-	-	-	-	1.5
Norway	Hvaler		Rural	Bidirectional	3.8	1989-1990	0.2	1.52	0	0	0	0	0	0
Norway	Flekkeroy		Rural	Bidirectional	2.3	1989-1990	0.3	1.38	0	0	0	0	0	0
Norway	Ellingsoy		Rural	Bidirectional	3.5	1988-1990	1.1	11.55	0	0	0	0	0	0
Norway	Valderoy		Rural	Bidirectional	4.5	1988-1990	0.9	12.15	0	0	0	0	0	0
Sweden	Windo		Rural	Bidirectional	0.5	1987-1991	1.6	3.2	0	0	0	0	0	0
Sweden	Søder		urban	Unidirectional	1.1	1987-1991	26	143	-	-	-	-	-	0.7
Sweden	Karra		Rural	Unidirectional	0.4	1987-1991	7.7	15.4	0	0	0	0	0	0
Sweden	Sorvik		Rural	Unidirectional	0.2	1987-1991	7.7	7.7	0	0	0	0	0	0
Sweden	Askloster		Rural	Unidirectional	0.3	1987-1991	4	6	-	-	-	-	-	19
Sweden	Fredhall		Urban	Unidirectional	0.2	1987-1991	36.8	36.8	0	0	0	0	0	0
Sweden	Karlberg		Urban	Unidirectional	0.5	1987-1991	9.6	24	0	0	0	0	0	0
Sweden	Klara		Urban	Unidirectional	0.5	1987-1991	9.6	24	-	-	-	-	-	15.5
Switzerland	Seelisberg*		Rural	Bidirectional	9.3	1981-87	4.2	273.42	-	-	-	-	-	2
Switzerland	Belchen*		Rural	Bidirectional	3.2	1978-86	11	316.8	-	-	-	-	-	1
Switzerland	San Bernadino*		Rural	Bidirectional	6.6	1968-87	1.7	224.4	-	-	-	-	-	5
Switzerland	Gothard*		Rural	Bidirectional	16.9	1981-87	3.7	437.71	-	-	-	-	-	3
Germany	Elbe		Urban	Unidirectional	3.3	1990-1991	37	244.2	13	6.3	9	24.6	22	9
France	Dullin		Rural	Unidirectional	1.5	1984-1991	7.3	87.6	1	1.6	0	0	1	1.3
France	Vuache		Rural	Unidirectional	1.4	1990-1993	4.8	26.88	1	3	0	0	1	2
France	Chatilon		Rural	Unidirectional	0.7	1990-1992	6	12.6	1	10.4	0	0	1	8
France	St. Germain de joux		Rural	Unidirectional	1.2	1990-1992	6	21.6	0	0	1	3.4	1	8.1
France	Fourviére	2.40%	urban	Unidirectional	1.83	1985-91	33	422.73						2
France	Croix Rousse	0	urban	Unidirectional	1.75	1985-91	24	462						2
France	Epine	0.50%	Rural	Bidirectional	3.1	1984-91	8.4	208.32	1	0.6	1	40	2	1.1
France	Mont Blanc*	2,4--0,5%	Rural	Bidirectional	11.6	1965-92	1.1	357.28						5
France	Chamoise		Rural	Bidirectional	3.3	1988-1992	8.5	140.25	1	1.5	5	22.6	6	6.8
France	Fréjus*	0.50%	Rural	Bidirectional	12.9	1981-91	0.9	127.71						9
France	Vieux-Port		Urban		0.6	1989-1994	23.9	86.04	6	2	0	0	6	1.8
Netherlands	Benelux		Urban	Unidirectional	1.3	1986-88	25	97.5	0	0	0	0	0	0
Netherlands	Coen		Urban	Unidirectional	1.2	1986-88	30	108	0	0	0	0	0	0
Portugal	Aqua Santas		Rural	Unidirectional	0.3	1991	7.6	2.28	0	0	0	0	0	0
Canada	Ville-Marie		Urban	Unidirectional	2.8	1988-1991	28.5	319.2	-	-	-	-	-	0.3
Canada	Hippolyte Lafontaine		Urban	Unidirectional	1.4	1987-1991	40	280	0	0	0	0	0	0
UK	Tyne		Urban	Unidirectional	1.7	1987-1992	9.7	98.94	-	-	-	-	-	25
USA	Brooklyn		Urban	Unidirectional	3.2	1989-1991	21	201.6	-	-	-	-	-	23
USA	Battery		Urban	Unidirectional	2.8	1989-1991	26.4	221.76	-	-	-	-	-	14
USA	Queens		Urban	Unidirectional	2.5	1987-1991	38.3	478.75	-	-	-	-	-	15
								6623.078						4.12
													Universal rate of fire per vehicle km	4.7
													Min	0
													Max	25
													stdev	6.47

D DESCRIPTION OF A CATASTROPHIC FIRE SCENARIO

The following imaginary scenario was written at the early beginning of this thesis to get some basic understanding on what situations might arrive, which factors need to be considered and generally what problems are to be expected when a fire occurs in a Road Tunnel like Hvalfjörður Tunnel. Reading this scenario might help the reader to understand how the consequence model was constructed. Numbers were estimated roughly but proved later to be very close to what theoretical calculations would have expected. It shows therefore perhaps that qualitative expert judgement might be just as good as quantitative and at least 100 times less time consuming!

The scenario

A transportation vehicle, fully loaded with heavy furniture, is driving south towards Reykjavik through Hvalfjörður Tunnel. Quickly after the vehicle has entered northern portal of the tunnel the driver realizes that he has to quickly slow down the vehicle because of the steep slope, he steps on the breaks but doesn't use the motor breaks to slow down the speed. Because the vehicle was extra heavy this day the tyres quickly get hot and they end up catching fire. The driver gets almost immediately aware when the wheels get on fire and stops when he has driven about 1 km into the tunnel. He steps out and decides to try to extinguish the fire. Fire extinguishers are placed 250 m apart in the tunnel but there are no signs between them leading to the shortest way. Unfortunately the driver ends up choosing the longer way and runs uphill about 150 m instead of perhaps 100 m downhill. It takes the driver only about 3 minutes to get to the extinguisher and back. When he arrives back to his vehicle he finds out that the fire has spread from the tyres to the cargo but he tries to extinguish it, unfortunately with no results. When he realises that he has no chance of extinguish the fire he grabs his cell phone and rings 112 to notify about the situation. The staff at the toll booth gets quickly a notification from 112 about the situation and immediately close the tunnel. The time from the fire started and until the tunnel was closed was estimated to be approximately 6 minutes.

As soon as the vehicle stopped a queue started to grow from the north side and also from the south side because of the smoke production which was travelling south at that time. The traffic was like on an average day about 2,3 vehicles/min entering the tunnel from both sides or roughly 12 vehicles in the tunnel at the same time with an average distance of 1037 m apart vehicles travelling in the same direction. The queue of vehicles travelling south is therefore about 2.3 veh/min/(2 sides) * 6min + 1000m/1037= 7.9 vehicles. The queue of vehicle travelling north was estimated as:2.3 veh/min/(2 sides) * 6min + 4770m/1037= 11.5 vehicles. A total of 19 vehicle were now in the risk zone or about 38 people (estimating 2 persons/vehicle)

Initially the wind in the tunnel was blowing at 1.5 m/s from north to south.

The vehicle fire was estimated to have evolved into a peak of 30 MW within 14 minutes. At the early stage the smoke went mostly in the same direction as the wind at roughly 1.5 m/s but as the fire grew the buoyancy force of the hot gases grew and when the burning effect reached 3 MW (4 minutes after the fire started) the buoyancy force took over and smoke started to move from south to north. The smoke had then travelled about 350 m south from the origin mostly in the upper part. When the turning point happened the smoke settled down in a matter of seconds and started now to draw from south to north at about 2.5 m/s speed. The air at the southern part from the fire cleared out in 5 minutes and all 14 passengers could reach safety. Drivers in the northern part got filled with panic as the smoke turned suddenly against them and tried to turn their vehicle back. 3 vehicles out of 10 vehicles managed to turn their vehicle around and reach safety but people in the rest of the vehicles (16*0.7=11) tried to reach the exit on foot. The time to travel 1000 meter uphill 8% slope in bad sight is about 1000m/(0.7 m/s) = 1428 seconds or about 24 minutes. These people had no chance of surviving 24 minutes in the toxic smoke and heat and all 11 died. When 30 minutes had passed since the fire started the Akranes fire department arrived at the scene. They had no chance of entering the tunnel due to the thick smoke facing them. 10 minutes later or 40 minutes after the fire started the fire brigade from Reykjavik entered and drove into the tunnel. The fire had started to decay when they arrived and they could thus quickly put the fire out.

E CALCULATION OF DANGEROUS GOODS ACCIDENT FREQUENCY

				min	max	most likely	Stdev	Average	Distribution
1	Road part no.		Tunnel						
2	Type of road, speed limit, km/h		70	70	70	70	0	70	None
3	Length, km	(a)	5.77	5.77	5.77	5.77	0	5.77	None
4	AADT	(b)	3667	3400	4000	3600			Triang
5	Traffic work, (a*b*365*10E-6)	(c)	7.7	-	-	-			
6	Number of accidents	(o)	7.7						
7	Accidents quotient	(o/c)	1.0				0.1	1	Normal
8	Proportion of single driver accidents	(Y)	0.60	0.3	0.9	0.6			Triang
9	Index for dangerous goods accident (see table 2.2)		0.14	0.1	0.18	0.15			Triang
10a	Number of dangerous goods vehicles		7.3	5	10	7			
10b	Number of dangerous goods vehicles/b	X	0.0020						
11	Number of marked dangerous goods vehicles in accidents		0.022						
12	Number of dangerous goods accidents		0.0031						
13	Expected number of years between dangerous goods accident		323						
	Number of dangerous goods accidents per million veh km		0.20						

A Monte Carlo simulation to account for uncertainty resulted in a wide range of possible frequencies. Figure 53 shows the distribution from the Monte Carlo simulation and a Normal Distribution with an average of 0.1992721 and standard deviation of 0.0332035 which the software BestFit from Palisade found out to fit best.

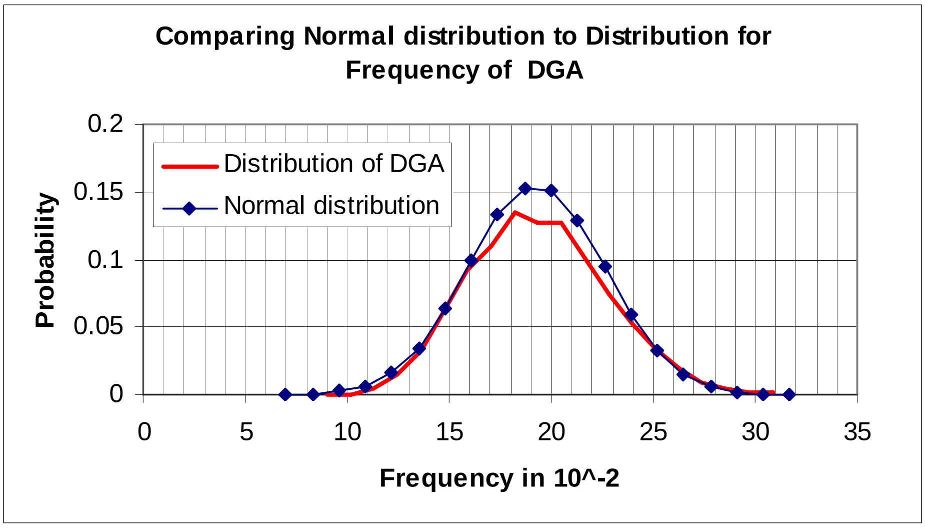

Figure 53. Density distribution for occurrence of Dangerous Goods Accidents

F CFD CALCULATIONS

The program used to carry out the CFD calculations was FDS version 3.1 from NIST (National Institute of Standards and Technology).

The model corresponded to the northern part of the tunnel. The tunnel was modelled in real size. Grid had to be rather coarse to reduce calculation time. Slope was modelled by using sloping g-vector. Wind, fans and the boundaries at the openings were adjusted until a steady wind of 1.5 m/s was obtained. Heat output was varied from 1.2 MW to 190 MW and the average velocity of smoke over 10 minutes registered. Results from these calculations are summarized in the figure below.

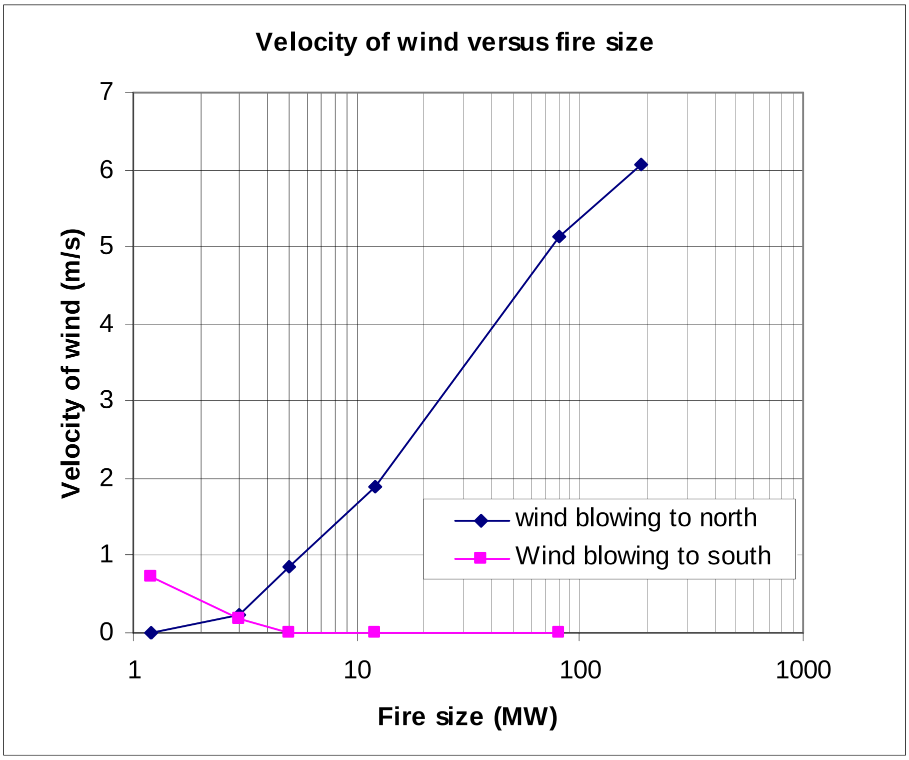

Figure 54. Wind velocity as a function of fire size. Results from FDS calculation

<u>A typical data file (1.2MW) is shown below.:</u>

```
&HEAD CHID='Gong_001',TITLE='Hallandi gong' /
&GRID IBAR=2000,JBAR=1,KBAR=6 /
&PDIM XBAR0=0,XBAR=2000,YBAR0=0,YBAR=13,ZBAR0=0,ZBAR=8  /
```

```
&TIME TWFIN=1200. /
&MISC    SURF_DEFAULT='CONCRETE',NFRAMES=1200,U0=1.5,GVEC=0.78,0,-
9.78,REACTION='HEPTANE'
    DATABASE='c:\nist\fds\database3\database3.data'
&SURF ID='burner',HRRPUA=100.0,RGB=1,1,0,PARTICLES=.TRUE. /
&OBST XB=997.0,1003.0,4,6,0.0,2.3,SURF_IDS='burner','INERT','INERT'/
&OBST XB=0.0,1982.0,0.0,1,0.0,8.0,SURF_ID='CONCRETE'/ RigtWall
&OBST XB=0.0,1982,12,12.0,0.0,8.0,SURF_ID='CONCRETE'/  LeftWall
&OBST XB=0.0,1982.0,0.0,13,7,8,SURF_ID='CONCRETE'/  Roof
&OBST XB=0.0,2000.0,0.0,13,0.0,1,SURF_ID='CONCRETE'/  floor

&SURF ID='BLOW',VEL=5,TAU_V=2 /
&VENT XB=50,50,3,8,4,6,SURF_ID='BLOW' /
&VENT XB=450,450,3,8,4,6,SURF_ID='BLOW' /
&VENT XB=750,750,3,8,4,6,SURF_ID='BLOW' /
&VENT XB=1500,1500,3,8,4,6,SURF_ID='BLOW' /
&VENT XB=1900,1900,3,8,4,6,SURF_ID='BLOW' /

&VENT CB='XBAR' ,SURF_ID='OPEN' /
&VENT CB='XBAR0',SURF_ID='OPEN' /
&VENT CB='YBAR' ,SURF_ID='OPEN' /
&VENT CB='YBAR0',SURF_ID='OPEN' /
&VENT CB='ZBAR' ,SURF_ID='OPEN' /

&SLCF PBY=0,QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
&SLCF PBY=0,QUANTITY='HRRPUV' /
&SLCF PBY=0,QUANTITY='MIXTURE_FRACTION' /
&SLCF PBY=0,QUANTITY='carbon monoxide' /
&SLCF PBY=0,QUANTITY='visibility' /
&BNDF QUANTITY='HEAT_FLUX' /

&PART DTPAR=0.5,AGE=1200,NIP=200 /
&BNDF QUANTITY='WALL_TEMPERATURE' /

&THCP XYZ=250,0,6.5,QUANTITY='TEMPERATURE' /
&THCP XYZ=250,0,6.0,QUANTITY='TEMPERATURE' /
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G GLOSSARY OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
ALARP	As Low As Reasonably Possible
BLEVE	Boiling Liquid Expanding Vapour Explosion
CEA	Cost Effective Analysis
CBA	Cost Benefit Analysis
CFD	Computational Fluid Dynamics
DGA	Dangerous Goods Accident
FDS	Fire Dynamics Simulator
FED	Fractional Effective Dose
HSE	British Health and Safety Executive
NIST	National Institute of Standards and Technology
PRA	Probabilistic Risk Analysis
QRA	Quantitative Risk Analysis
VCE	Vapour Cloud Explosion