Quantitative Risk Analysis Procedure for the Fire Evacuation of a Road Tunnel

-An Illustrative Example

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Abstract
This report describes the methodology for performing a quantitative risk analysis for a unidirectional road tunnel. By using representative accident scenarios, a basic queue model and performing an evacuation analysis the amount of casualties for each scenario can be estimated. By using the described methodology it gives the decision-makers a good idea of the risk level in the tunnel. The results can suitably be used by decision-makers when deciding upon which resources should be spent on further safety installations for the tunnel.

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Sammanfattning

I denna rapport presenteras en metod för att genomföra en kvantitativ riskanalys för en vägtunnel med enkelriktad trafik. På grund av den stora mängden tunnelolyckor som inträffat med ödesdigra konsekvenser den senaste tiden har ämnet tunnelsäkerhet blivit ett hett ämne. Det ägnas mer resurser åt att höja säkerhetsnivån i befintliga tunnlar samt att bygga och projektera ”säkrare” tunnlar. Metoden som presenteras i denna rapport kan användas som ett verktyg för att genomföra en analys och få en uppfattning om risknivån i den specifika tunneln.

För att ge läsaren lite bakgrunds information har en kortfattad beskrivning av vad riskanalyser på olika nivåer skall innehålla inkluderats. Innebörden av kvalitativa, semikvantitativa och kvantitativa riskanalyser beskrivs, samt ett exempel enligt Patè-Cornell på hur detaljerings nivå och behandlingen av osäkerheter skiljer sig på de olika nivåerna.

I och med att alla tunnlar skiljer sig från varandra är det viktigt att beskriva den tunneln som skall analyseras. Utifrån den beskrivning samt information om existerande säkerhetssystem och typ/mängd fordon som använder tunneln har representativa olycksscenarier tagits fram. I denna analys har olyckor med följande fordon analyserats,

- Bilar
- Tunga Lastbilar
- Transport av brandfarlig vätska (bensin)
- Transport av tryckkondenserad brandfarligt ämne (propan)
- Transport av explosivt ämne (TNT)

Frekvensen för olyckor med ovanstående fordon har bestämts. VTI modellen har använts för att bestämma frekvensen för farligtgods transporterna.

En konsekvensanalys där förväntade antalet omkomna uppskattas har genomförts för samtliga scenarier. För de scenarier som har förknippats med en designbrand har en modell som är baserat på fraktionella effektiva dosen (Fractional Effective Dose) använts. I denna modell tas hänsyn till de toxiska ämnen som brandgaserna innehåller och den effekt de har på de utrymmande människorna i tunneln. Genom att definiera kritiska värden för de olika toxiska substanserna har denna modell använts för att beräkna hur långt människor med olika utgångslägen hinner gå innan kritiska nivåer uppnås. Dessa beräkningar har sedan använts för att uppskatta antalet omkomna. Hänsyn har också tagits till den direkta strålningen från flammorna och effekten den har på människor som vistas i närheten av branden. På grund av bristen på vetenskaplig information gällande fenomenen gasmolnsexplosion (Vapor Cloud Explosion), BLEVE och ”Flash” bränder har konsekvensberäkningarna för dessa fenomen baserats på vissa antaganden som gjorts av författaren. Slutligen har effekten på människor i en tunnel av en tryck våg till följd av en TNT explosion analyserats.

En utrymningsanalys som baserats på givna gånghastigheter och reaktions och beslutstider har genomförts. Antalet människor i tunneln efter olyckan har inträffat har beräknats med hjälp av en enkel fordonskömodell. Därefter har tiden som krävs för att utrymma olika delar av tunneln beräknats.

Efter att ha uppskattat frekvensen och konsekvensen av samtliga scenarier har resultatet redovisats i form av en riskprofil i ett F/N diagram. Riskprofilen kan då jämföras med riskkriterier och resultatet kan tolkas som acceptabelt, oacceptabelt eller acceptabelt under förutsättningar att vissa riskreducerande åtgärder genomförs.

Avslutningsvis beskrivs vissa säkerhetssystem som kan integreras i en tunnel och hur effekten av dessa kan påverka resultatet i en analys som genomförs enligt den metodiken som beskrivs i denna rapport. Säkerhetssystemen som beskrivs är rökventilationssystem, fasta släcksystem och ett integrerat ledningssystem för säkerhet.

Summary

This report presents a method for performing a quantitative risk analysis for a unidirectional road tunnel. Due to the many recent tragedies in tunnels, the topic of tunnel safety has become very relevant, and more resources are being spent to improve the safety levels in tunnels. The methodology presented is a good tool for performing initial estimations of the risk level in a certain tunnel.

A description of the different levels of a riskanalysis is include to give the reader background information about what is included and how detailed analysis on different levels should be. Analyses ranging from a qualitative to a quantitative analysis are discussed and the advantages of performing a quantitative analysis are made clear.

Since every tunnel is different it is important to describe the tunnel that is being analysed. Considerations to existing safety systems should be a natural part of the analysis. Based on the tunnel description and the vehicles that use the tunnel, representative scenarios have been developed. Accident scenarios involving the following vehicles have been considered in the analysis.

- Car
- Heavy Goods Vehicle (HGV)
- Gasoline transport
- Propane transport
- TNT (explosive) transport

The frequency per year of each scenario occurring has been determined. In order to determine the frequency per year for the hazardous goods transports (gasoline, propane and TNT) the Swedish VTI model has been used.

The estimated number of casualties for each scenario has also been determined. For the scenarios where design fires have been assigned a model based on the Fractional Effective Dose has been used. In this model consideration is taken to the different toxicants that are present in the smoke in the tunnel and the effect they have on the escaping people. By assigning critical values, the model has been used to calculate how far people initiating from different areas in the tunnel can proceed before they are subjected to critical conditions. Based on these calculations the amount of casualties have been calculated. Consideration has also been taken to the direct radiation from the flames and the effect it has on the people it the direct vicinity of the fire. Due to the lack of knowledge of the phenomena Vapor Cloud Explosions (VCE), BLEVE and Flash fires certain assumptions have been made when determining the amount of casualties for these scenarios. At last the effect a pressure wave resulting from a TNT explosion in a tunnel has on humans has been calculated.

A separate evacuation analysis has been performed. First the amount of people in the tunnel has been determined using a simple queue model. Thereafter the time until people have evacuated different areas of the tunnel has been calculated using predetermined premovement times and set walking rates.

Having determined the frequencies and consequences (in terms of number of casualties) the final result has been illustrated using an F/N curve. Here the acquired F/N curve can be compared with set risk acceptance criteria, and the results can be viewed as acceptable, unacceptable or acceptable given certain modifications or risk reducing procedures.

Finally certain safety systems are evaluated closer, a description of the safety system as well has how it can potentially affect the result when performing a quantitative risk analysis according to the described methodology is discussed. The safety systems that are discussed are; smoke ventilation systems, fixed suppression systems and a tunnel safety management system (SMS).

1 Introduction

1.1 Background Information

The following topic has been chosen in collaborating with Ernst Basler+Partner in Zollikon, Switzerland. The topic of tunnel safety has become center of attention lately due to many recent events leading to catastrophic consequences due to tunnel fires. Among those being the fire in the Mont-Banc tunnel in France and the Tauern Tunnel in Austria.

On the 24 March 1999 a truck loaded with margarine and flour caught fire in the Mont-Blanc Tunnel between Chamonix, France and Aosta, Italy. The fire developed very quickly causing the death of 39 people. Then again on the 29 May 1999 an accident, involving multiple vehicles, in the Tauern Tunnel in Austria caused a fire leading to 12 deaths and many injured. It is accidents like these that make people aware of potential dangers that are somewhat unnoticeable, people start questioning the level of safety that is provided in the infrastructure, and demand that something be done to improve the level of safety. Since the occurrence of these accidents it is evident that more resources are being spent on developing safety systems and strategies to increase the overall safety in tunnels. This paper presents a method for analysing risks in a unidirectional road tunnel.

1.2 Aim

The aim is to develop a systematic approach to performing a quantitative risk analysis (QRA) for a defined road tunnel. The evacuation process will be analysed and the evacuation possibilities for representative scenarios determined. Additionally the effects of different safety systems will be evaluated. The evaluation will be based on qualitative reasoning regarding the positive effects that the safety system will add to the people in the vehicles in the tunnel.

1.3 Restrictions

The methodology developed in this paper is designated for a tunnel as described in chapter 3 of this paper. The methodology can be used for other purposes but one should be aware of the reasoning behind each section. The methodology used represents a great simplification of reality and one should be aware of this when interpreting the results. That is to say that the results are only indicative and not a precise value in any manner. Only the lethal effects on humans has been of interest when analysing the different scenarios as described in the paper, no consideration has been taken to material damage that might be caused as a result of the different scenarios that have been analysed.

1.4 Method

The method that has been used in this paper is one that is used frequently when evaluating and justifying performance based building codes. A vehicle queue model has been designed and used to estimate the amount of people that might be affected by an accident in a specific tunnel. The time needed for these people to complete evacuation from different areas in the tunnel has then been calculated using simple calculations based on predetermined pre movement times and set walking rates. Using the concept of Fractional Effective Dose (FED), the walking distances in the case of fire for different people initiating from different areas in the tunnel has been calculated.

Each scenario has been further analysed and an event tree showing possible outcomes for each relevant scenario has been constructed. A study on the frequency of each scenario has been carried out. The final result has been illustrated using an F/N curve.

The effect that different safety systems have on the outcome in the different scenarios has been qualitatively discussed. A suggestion on how a ranking system for different safety systems should be developed is further discussed. This in order to help the decision-makers when deciding on what safety systems to install.

2 Different Levels of Risk Analysis

When the point has been reached where it has been recognized that a certain technical installation could evolve events that might lead to unfavorable consequences and this needs to be further investigated, one is faced with the question of how detailed does this specific event have to be analysed. The questions that are to be answered in the following analysis are:

1. What can go wrong and why?
2. What is the likelihood (frequency) that a certain event will happen? How bad could they be (consequences)?
3. What can we do about it?

In answering these questions one has to determine how detailed the study has to be. This is usually done by pragmatically estimating the risk level associated with the specific event, determining specific hazards, and determining what information and resources are available.

Regardless of the level of the risk analysis, certain key aspects should always be included and clearly documented; which can be summarised in the following points:

- Clear definition of the scope/restrictions of the study.
- Identification and evaluation of hazards associated with the study.
- Analysing (and quantifying) risks.
- Tolerability assessment, how tolerable is the system (identifying risk criteria)?
- Risk reduction (if necessary).

These points can be summarised in figure 2.1.

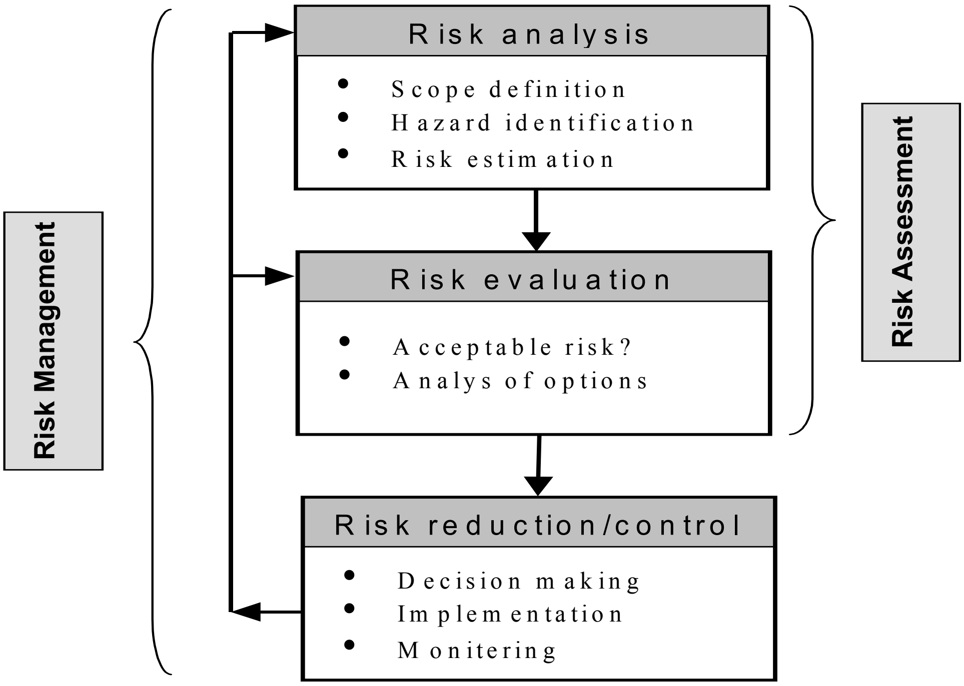

Figure 2.1- The Components of Riskmanagement /IEC, 1995/

Cost-benefit analysis can be considered as being another level of risk analysis, or a tool to assist decision makers in making the ”right ” decisions. This enables the decision maker to compare different solutions by assigning money value to each choice.

Various people and organisations throughout the risk management field in the world have defined many different definitions of the scope of different level risk analysis. Generally these can be divided into qualitative, semi-quantitative and quantitative analysis. A short description of each will follow.

One of the major problems with both qualitative and quantitative risk analysis is the lack of consistency. Since the definition of these different levels of riskanalysis are different in different fields and areas of the world it should be clearly specified what a specific riskanalysis should include. The scope of the risk analysis should be clearly defined at an early stage in any project to minimise the risk for confusion between the different parties involved.

2.1 Qualitative

This is usually considered as the first level of a risk analysis to determine whether further analysing is necessary and in what area the resources should be concentrated in order to provide the most value. It is a tool used by management to determine where to allocate the resources on evaluation techniques. Thus it can be said to be a useful tool on systems that present a relatively low risk. Usually some sort of ranking system is used to determine what aspects of a technical system needs further investigation and what parts or sub-systems can be considered ”safe enough”. Simple risk matrices are often used where frequencies and consequences are divided into categories such as High, Medium and Low.

Qualitative risk analysis results are mainly derived from deterministic hazard analyses combined with qualitative evaluations of frequencies and consequences of a specific event. Tools such as Failure Modes and Effects Analysis (FMEA) and Hazard and Operability Studies (HAZOP) /Kemikontoret, 2001/ are used to determine significant initiating events/scenarios along with the effects that available safety systems have on the outcome of the scenario. Qualitative event trees or similar methods are then used to determine the relationship between initiating events and the outcome due to the presence of different safety systems, from these results qualitative frequency estimates can be made.

A qualitative analysis will typically include a discussion of the methodology used, a presentation and discussion of the prioritisation results, and a discussion of further works and risk reducing actions /Kolluru, 1996/

2.2 Semi- Quantitative

In a semi-quantitative analysis events are identified and ranked on some sort of predetermined risk scale. The risk scales can be divide into various categories and the event is categorised depending on the risk level that it is associated with. The event can also be placed in a risk matrix, where the frequency of the event is considered (ie high, medium or low) together with the consequences that are a result of the event (ie serious, extensive or catastrophic). This approach combines qualitative methods with established risk assessment techniques and it is a relatively simple and effective approach This form of analysis give decision makers more information regarding where to spend resources on risk preventive measures.

2.3 Quantitative

A quantitative analysis can generally be considered as being the most objective. This type of analysis is usually the most detailed and therefore requires the most time and resources. Frequencies and consequences are quantified and can thus relatively easily be compared and ranked. Objective risk acceptance criteria can be implemented and thus quantified risks can easily be classified as acceptable or not acceptable. This form of analysis usually includes some form of uncertainty analysis.

This paper presents a method for performing a quantitative risk analysis for a road tunnel. The method that has been developed includes the basic elements of a quantitative risk analysis; hazard identification, quantification through consequence analysis and probability or frequency estimation and risk determination and reporting /Kolluru, 1996/.

The hazard identification element of this paper includes the identification of representative accident scenarios in the tunnel, this is further discussed in section 4. Consequence analysis have been carried out on the scenarios that have been defined as well as frequency estimations. Thereafter the results have been presented in an F/N curve, which illustrates the societal risk present in the tunnel. This is a measurement which shows the relationship between the frequency of an event happening (F) and the consequences in terms of the amount of casualties (N).

Qualitative methods are usually incorporated into quantitative analysis. This is usually done when for example suggesting risk reducing procedures. The risk reducing procedure will usually lower the risk by either reducing the frequency or consequence of a negative event. Some risk reducing system are qualitatively discussed in section 8.

2.4 Treating Uncertainty

When doing a risk analysis the following points regarding uncertainty in a QRA should be considered.

- Clear definition of the uncertainties associated with a certain process or calculation.
- The effects of a parameters uncertainty to the end result.
- How these uncertainties are to be ”weighed” when comparing to acceptance criteria.
- How are the uncertainties to be illustrated and effectively communicated?

There is no definite way of answering these questions. However certain models or uncertainty ranking systems have been developed and should be used as a tool to get a clearer image of the meaning of uncertainty. This should be taken into consideration when interpreting results from different types of analysis. In many cases one can see that results have been interpreted in a too precise manner.

It is important to make a distinction of what type of uncertainty that one is dealing with. Generally there are two types of uncertainties, namely *stochastic uncertainty* and *state-of knowledge uncertainty.* In short stochastic uncertainties or sometimes called aleatory uncertainties can be viewed as being the variation in results from a stochastic process (such as flipping a coin) under identical conditions. These are uncertainties that generally cannot be reduced by a deeper analysis when determining frequencies in the following analysis one is usually faced with this type of uncertainty While state –of knowledge uncertainties or epistemic uncertainties result from the lack of complete information about the object/system that is being analysed, obtaining more data/information can usually reduce this factor. The uncertainties that are involved when performing the consequence analysis in this paper are generally of this type. A model developed by Elisabeth Paté-Cornell is an example of different levels of risk analysis and explains how uncertainties are treated on each level /Paté-Cornell, 1996/.

2.4.1 Paté-Cornells Six Levels of Treating Uncertainty

There is almost always some degree of uncertainty in an analysis, but to what extent do these uncertainties have to be studied? Paté-Cornell answered this question by defining six levels of how uncertainty should be treated. She considers everything between a decision where uncertainties are not quantified at all to complex decisions where it is very helpful to have a structured approach towards quantifying the uncertainties that are involved. She defines six levels of risk analysis, ranging from level 0 to level five.

In a level 0 analysis no form of quantification is made, it is a qualitative analysis where potential hazards are identified. This is a sufficient level if the decision of what type of risk reducing procedure is clear given the potential hazard and low costs for the implementation of the risk mitigation measure. Failure Mode and Effect Analyses (FMEA) and Critical Item List (CIL) are examples of analysis that can be used for engineering systems on level 0. FMEA is based on fault tree analysis and allows different components that might lead to system failure to be analysed, identifications of where redundant systems are necessary can thus be suggested. CIL does this in a similar manner by listing components according to how critical they are in a system, the most critical systems should be equipped with some form of redundant system. These type of methods are simple and require relatively small resources compared to probabilistic methods, however they do not permit a way of calculating the effectiveness of the proposed risk mitigation measures.

A level 1 analysis considers the worst-case scenarios without considering the probability of this event. This level is in practice only applicable to decisions that can be supported by calculating the worse loss. It is however not very useful because one can always consider circumstances which could lead to even worse results.

Level 2 represents a method where the worst possible cases or “worst credible” cases are considered and based on this some sort of upper plausible bounds can be established. This is a method that attempts to create conservative results but does not ensure maximum risk reduction for the money spent. It is difficult to judge the conservatism in the estimates that are made on this level since what might seem as a conservative assumption to one part might not be viewed as conservative by a second part. It is also difficult to compare different risks that have been calculated on this level because risks that have been calculated using worse possible scenarios or upper plausible bounds do not have to be the same as the risk that would have been calculated using average or mean values.

In a level 3 analysis best estimates or central values (ie mean value) of the variables are used to create a best estimate or central value of the outcome. In order to achieve a best estimate value the most probable scenarios or events are chosen and for each scenario maximum-likelihood estimates of the parameters are made. Using central values in the analysis provides a reasonable balance to plausible upper bounds, as used in level 2. The risk calculations are still based on single point estimates in this level and even though a mean value is used the effects of the uncertainties can not be viewed directly in the deterministic result that is achieved.

In a level 4 analysis probabilistic risk analysis is used to obtain a distribution of the probabilities for the different scenarios/events that have been defined. The distributions are based on best estimates of the models used and the input parameter values, therefore this level does treat uncertainties, but does not differentiate between aleatory and epistemic uncertainties. This level permits a representation of the risk in the form of a complete distribution of the potential losses. Since the result is presented in one risk curve it is impossible to see the effect of epistemic uncertainties in the final result.

Level 5 presents a method where a distinction is made between the two types of uncertainties. Aleatory uncertainties are viewed the same way as in a level 4 analysis, however to get an idea of the epistemic uncertainties experts are used to provide an assessment of the risk based on their knowledge and preferred models. The difference in results can thus be viewed directly in the risk curves from each expert and gives an good idea of the epistemic uncertainties involved in the analysis /Paté-Cornell, 1996/.

2.4.2 Treatment of uncertainty in this analysis

The analysis that has been carried out contains many uncertainties in different areas. It is often the lack of resources (time and money) that result in uncertainties, thus these are epistemic uncertainties and could be greatly reduced by increasing the resources. An assumption regarding future events always contains some degree of uncertainty, the degree of uncertainty can usually be reduced by performing an in depth study about the specific assumption.

In all levels of analysis it is essential to remember how the numbers were generated, what they represent and what they can be used for. It is of importance that the results always be viewed critically and that the background reasoning behind the methodology is understood by the person interpreting the results. As the aim of this paper is to develop a methodology for performing a quantitative risk analysis on a unidirectional road tunnel the uncertainties that are involved in the consequence analysis and in the determination of the frequencies have not been incorporated in the final risk presentation. The analysis that has been performed is thus comparable to a level 3 analysis on Paté-Cornells scale. A level 4 analysis has however been carried out when determining the frequency for a hazardous goods accident resulting in a spill (see Appendix B). The uncertainties that were achieved in this analysis have not been propagated in the remainder of the analysis and can therefore not be viewed in the final results. The level 4 analysis that has been carried out does however give the reader an idea of the high level of uncertainty that is involved with an analysis of this kind.

2.5 Appropriate Risk Analysis Level for a Tunnel

As previously stated there is a lack of consistency in how a risk analysis for a road tunnel should be carried out. There is of today no existing guidelines on how a risk analysis should be carried out /PIARC, 1999/. This thesis provides an example of a methodology that could be used when analysing the risks to humans using a road tunnel. It is however up to the decision-makers or legal authorities to decide how detailed an analysis should be. The level of the analysis also depends on, as stated above, the decision that the analysis is meant to be a basis for. If for example a decision regarding the installation of hand held fire extinguishers requires an analysis an appropriate level might be level 0, however if the decision of weather a tunnel should be built in a certain area or not requires an analysis level 4 or 5 would most likely be appropriate.

Due to the increasing amount of tunnels that are being built and the amount of accidents that have occurred in existing tunnels, the issue of safety in road tunnels should be an issue that has a high priority in every new tunnel project. The advantages of the tunnel have to been weighed appropriately against the risks that are associated with the building of a tunnel and using it as a means of transport. Alternative options to building a tunnel should also be considered; this should be a natural part of any risk analysis that is the basis for a decision of whether or not a tunnel should be built. Due to the fact that every tunnel project will be different it is difficult to make generalisations, and state that every risk analysis that is performed on a tunnel project and is the basis for a decision of whether the tunnel should be built or not should be of a certain level. This increases the importance of having a well-established methodology when approaching the problem. It is therefore difficult to generally say how detailed a risk analysis should be for any certain tunnel without further investigation. However it can generally be said that the more complex the tunnel system is the more detailed the analysis will have to be.

Another important factor when discussing what level of risk analysis that should be carried out is the existence of predetermined risk criteria. If the society where the tunnel is being built has developed definitions of what acceptable risks are, a quantitative risk analysis can be carried out and the final results will either be above or below the acceptable risk criteria. Based on this various risk reducing systems can be suggested to reduce the risk to a tolerable level. If no such criteria exist, there will be an obvious conflict when discussing the quantitative results.

In this thesis a tunnel has been defined and a quantitative risk analysis has been carried out. The purpose of this is to develop the methodology of performing a quantitative risk analysis, the results will therefore not be a basis of whether the tunnel should be built or not. A short interpretation of the result has however been included.

An analysis according to the methodology that has been developed should ideally be carried out in the planning process of the building process. The earlier the risks are identified the easier they are to assess and reduce.

3 Definition of Tunnel

3.1 General Information

Due to the many aspects and characteristics of a tunnel that can vary the tunnel that was going to be studied had to be clearly defined. Many of the aspects clearly have a result on the consequences in case of an accident.

The tunnel that has been studied in this thesis is one of the tunnels that is part of a tunnel system, which consists of two tunnels each with two lanes and one-way traffic. The tunnels are connected every 360 meters with airproof passageways. The tunnel is straight and has no inclination. More information about the tunnel is found in table 2.1.

Tunnel Length	1100 m
Tunnel Height	7.5
Tunnel Width	2 lanes each 3.5 m 2 side lines each 0.25 m Emergency walkways on each side 1.2 m Total width 9.9 m
Cross sectional area	74.25 m^2
Traffic Loads	44 300 vehicles/24 h
Speed Limits	80 km/h, Trucks are forbidden to overtake

Table 2.1- Tunnel information

3.2 Evacuation Possibilities

The tunnel is equipped with passages connecting the two tunnels, these passages are located every 360 meters, making a total of three cross passages in the tunnel system. These passages are equipped with airtight doors preventing smoke spread from one tunnel to the other.

On each side there is a 1.2 m wide emergency walkway, emergency lighting is installed at a height of 1.3 m above the walkway.

3.3 Ventilation System

Each tunnel contains a ventilation system that comprises 8 longitudinal ventilators each with a capacity of 28 m^3/s. During normal conditions carbon monoxide and light condition sensors regulate the ventilation capacity. Each tunnel contains 3 CO sensors and 3 light sensors.

In the case of a fire the ventilation system is controlled by the fire detecting system, the capacity is adjusted depending on where the fire is detected, current traffic situation, and wind conditions in the tunnel. The basic idea of the smoke ventilation system is to delay smoke spread in the direction opposite of initial traffic flow. This is based on the idea that any vehicles situated in front of the accident will continue out of the tunnel and will thus not be in any direct threat to a potential fire, the smoke will thus be ventilated in this direction, giving the vehicles behind the accident maximum time to evacuate before smoke spreads to this area. How well this theory works in reality obviously depends on factors such as; functioning ventilation system, the reliability of the systems controlling the ventilation system, ventilation capacity is sufficient to prevent smoke spread in unintended direction, the fire is detected at an early stage and the ventilation system is activated immediately.

3.4 Fire Detection/Suppression Systems

Manual ”push button” fire alarms are situated regularly throughout the tunnel (at least every 180 m). An automatic fire detection system is also available. Video cameras throughout the tunnel enable a fire to be detected manually from the control room.

Two 6 kg hand held fire extinguishers are located every 180 m throughout the tunnel. A 6 bar water pipe runs through the tunnel, the first 300 m from each end is heated to prevent freezing. The water is supplied by a nearby reservoir and is sufficient for the fire brigade.

3.5 Communication Systems

Emergency call points are installed every 180 m throughout the tunnels as well as at every passage way between the tunnels and at the beginning and end of each tunnel. These emergency points also contain loud speakers through which information can be received from the control room. The tunnel is equipped with radio transmitters enabling police and fire brigade to use their communication devices; radio transmitters enabling the use of mobile phones are also available.

Information boards are situated in front of and regularly throughout the tunnel providing the vehicles with information regarding speed limits, traffic conditions, warning for fog or ice, these information boards are also used for regulating the traffic in case of an accident.

3.6 Drainage system

The drainage system consists of a channel, which leads contaminated water to a pool, here the contaminants can be collected and taken care of accordingly. The system is closed, to minimise the chance of polluting the surrounding environment.

3.7 Warning Signage

The tunnel is equipped with various warning signs that are used to warn the people in the vehicles of different threatening situations. 40 meters before entering the tunnel from either direction there is a traffic light showing a green or a red light as well as a gate which is controlled by the tunnel operator. As soon as a threat is detected in the tunnel, the red light is activated (and eventually the gate closed) and vehicles are assumed to stop outside the tunnel. Changeable traffic signs with either a green arrow, yellow arrow or a red cross are located at the following distances from the tunnel entrance; 10, 310, 610, 910 meters. Changeable traffic sign showing; fog warning, ice warning, and overtaking prohibited are located 800 m after entering the tunnel.

4 Scenarios to be analysed

4.1 Risk identification

A simple procedure based on a literature study on information from tunnel fires and how they initiated and developed has been the basis of the risk identification that has been carried out. More complicated analysis methods such as hazard and operability (HAZOP) analysis and What if? analysis /Kemikontoret, 2001/ could potentially be carried out on the specific systems that are integrated in the tunnel. However the greatest threat has shown to be the vehicles travelling through the tunnel / Alan, 1998/, where fires occur mainly due to brake overheating, electrical defects, and other defects leading to self-ignition. Studies have also shown that a majority of the accidents resulting in vehicle fires are caused by human error /Astra, 2000/. Thus varying scenarios have been chosen to represent the majority of the possible vehicles that might use the tunnel.

4.2 Design Fire

Each scenario that has been chosen will be associated with a certain design fire. The growth rate and maximum size of the design fire has been chosen in such a manner as to represent an actual fire scenario involving the relevant type of vehicle. The uncertainties involved in this step are large depending on the great variation of vehicles. It is based on this design fire that the conditions in the tunnel will be calculated. The design fires have generally been chosen to represent the worse type of vehicle, that is to say the vehicle that will result in the largest and fastest developing fire. By doing this the end result will tend to under predict the time until hazardous conditions are reached, hence resulting in conservative results. The question of when the heat release rate of a fire starts to decline is not of top priority in this analysis. It is the developing stage of the fire that is of crucial importance when analysing the evacuation process. When the maximum HRR has been reached the HRR will be assumed to remain constant for a predetermined period of time. Thereafter the design fire will start to decline. The design fire for each scenario has been determined in section 4.3 below.

4.3 Scenarios

As a result from the risk identification analysis the following scenarios have been chosen, these scenarios have been chosen as representative scenarios. It is hard to predict exactly how a fire will develop in a tunnel due to the numerous sight specific conditions that influence the situation.

4.3.1 Car

There have been many full-scale tests performed on passenger cars, so information on heat release rates (HRR) from this type of fire is available for a large variation of passenger cars. The HRR of a car fire depends on the construction material used in the car, tests have shown that modern cars from the 90s generally tend to release more energy than those manufactured earlier /Joyeux, 1997/.

Test results suggest that the approximate total energy content of a passenger car will vary between approximately 3 to 9 GJ /PIARC, 1999/. Peak HRR during test with one car have generally been recorded at 3-5 MW however peak release rates up to 9 MW have been recorded due to ruptured petrol tanks resulting in rather large pool fires /Joyeux, 1997/.

For the purpose of determining the consequences to humans resulting from a car fire the following design fire will represent a fire resulting from an accident involving two to three cars.

$$Q(t) = \alpha\, t^2$$ **Equation 4.3.1.1**

for $t \leq 20$ minutes. Based on a maximum heat release rate of 8 MW after 20 minutes the value of $\alpha = 0.0056$ kW/s^2. *Q(t)* will remain constant (8MW) for $20 < t < 40$ minutes. Thereafter the heat release rate will decrease according to the following equation:

$$Q(t) = Q_{\max} e^{-\beta\left(t - \sqrt{\frac{Q_{\max}}{\alpha}}\right)}$$ **Equation 4.3.1.2**

Where $\beta = 0.0007$ s^{-1} /Bergqvist, 2001/.

4.3.2 Heavy Goods Vehicle

This is a difficult category as the type of ”heavy goods” can vary drastically. Tests included in the EUREKA 499 test series have included a measure of the HRR of a Simulated Truck Load (STL), which consisted of 2212 kg of densely packed wooden pallets, 310 kg plastic mixed with the pallets and 332 kg of rubber tires. The total calorific value of this fire load was estimated to approximately 65 GJ. Another test with a load of 2000 kg upholstered furniture was estimated to have a total calorific value of 87 GJ. The ventilation conditions during the test have a great influence how a fire will develop. The fire test with the HGV carrying upholstered furniture was carried out with forced ventilation of 6m/s until 13.5 minutes, at this time the ventilation was shut off and the HRR of the fire was reduced from 120 MW to 42 MW in 3 minutes. After 16.5 minutes the ventilation was turned on resulting in an air velocity of 3 m/s. This caused the fire to reach a peak HRR of 128 MW within 4 minutes of restarting the ventilation /PIARC, 1999/.

HGVs have been involved in many of the recent tragic tunnel fires. In the Channel tunnel fire a similar situation to the one described above with the upholstered furniture occurred. The fire initially involved three HGVs, and when the supplementary ventilation system was activated, to prevent smoke spread in one direction, the fire quickly spread to another seven HGVS. This fire caused peak HRR of approximately 350 MW (average HRR for three hours about 150 MW, using the value 13.1 MJ/kg air to calculate the max HHR).

In this scenario two different design fires will be analysed. One will consider the scenario where the ventilation system fails causing fire spread to potential other HGVs behind (upstream) the initial fire. The other scenario will assume that the ventilation systems is working preventing fire spread to vehicles queued up behind the accident. The following two design fires will be used for these two scenarios Q_{max}=20 MW @ 15 minutes after fire ignition and Q_{max}= 120 MW @ 30 minutes for the scenario when the ventilation fails causing fire spread to another HGV.

The design fires will have the following heat release rates:

HGV 1: $Q(t) = \alpha\, t^2$ for $t \leq 15$ min, $\alpha = 0.025$ kW/s^2

HGV 2: $Q(t) = \alpha\, t^2$ for $t \leq 30$ min, $\alpha = 0.037$ kW/s^2

For HGV1 $Q(t)$= 20 MW for 15 < t < 60 minutes, and for HGV2 $Q(t)$= 120 MW for 30 < t < 90 minutes. After the peak heat release rate (Q_{max}) has been reached it will be assumed that the HRR will decrease according to the following equation:

$$Q(t) = Q_{\max} e^{-\beta\left(t-\sqrt{\frac{Q_{\max}}{\alpha}}\right)}$$

Where $\beta = 0.0007$ s^{-1} /Bergqvist, 2001/.

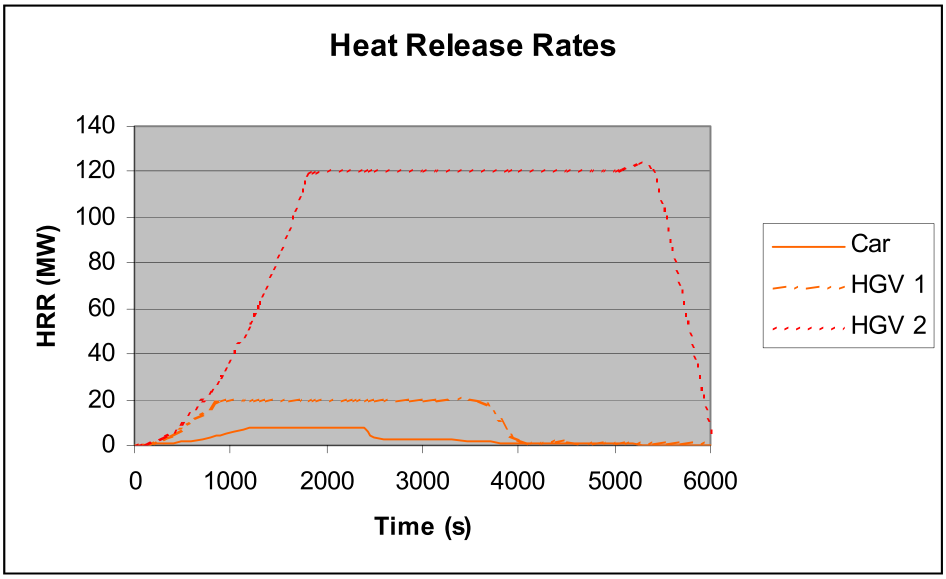

Figure 4.3.2.1- Design Fires

4.3.3 Hazardous Goods Transport

Hazardous goods transports present a great threat to tunnel safety, due to the potential rapid-fire development in the case of an accident and the effect of the release of various toxic substances. The most frequently transported hazardous goods will be analyzed, in this case gasoline and propane. The effect of an explosion in a tunnel will also be further investigated (see Appendix A).

Gasoline is by far the most frequently transported hazardous goods (68 % of the total hazardous goods transported on road (Statistical information from Germany for 1995) /Ernst Basler, 2001/ and thus presents one of the greater threats. A scenario based on an accident with the transportation of 20 cubic meters of gasoline will be used as a representative accident for this type of hazardous goods transport. The different design fires used for this scenario are further described in Appendix D. Since this scenario deals with gasoline all fires will develop very quickly, it has been assumed that the design fires will reach their maximum HRR after 45 seconds. Thereafter the HRR will remain constant.

A representative accident with a vehicle containing a liquefied gas such as propane will also be investigated. The effects of ignition of propane in a confined area such as a tunnel are uncertain.

The effects of an explosion of a vehicle containing 1000 kg of TNT will also be investigated. In this case the effects of a pressure wave on humans will be analysed (see Appendix A).

Scenario	Q_{max} (MW)	*Comments*
Passenger Car Fire	8 @ 20 min, t_{max}= 20 mins	
Heavy Goods Vehicle (1)	20 @ 15 min	Functioning Ventilation
Heavy Goods Vehicle (2)	120 @ 30 mins	Ventilation failure
Gasoline Fire		
Propane	**See event tree for different scenarios (Appendix D)**	
TNT (explosion)		

Table 4.3.3.1- Representative Scenarios

4.3.4 Determining Frequencies

A study has been performed on available information regarding statistical information on frequencies of accidents for the relevant scenarios. Information resources from Switzerland /BUWAL 1999/, Germany /Ernst Basler, 2001/ and Sweden /Räddningsverket, 1996/ have been investigated. It can generally be said that there is no uniform procedure of quantifying the frequencies for a specific scenario. The process of quantifying the frequencies for a certain scenario happening for the purpose of using them in a quantitative risk analysis (QRA) is therefore attributed with a certain level of both epistemic and aleatory uncertainty. There will always be a certain degree of aleatory uncertainty in the frequencies since it is a prediction of how many accident are going to happen. The level of epistemic uncertainty can however to a certain degree be decreased by doing a more detailed frequency analysis. This could for example involve doing actual measurements on how many and what type of vehicles will be travelling through the tunnel. It should be stressed that the main aim of this report is not to perform an in depth study on how relevant frequencies are chosen.

Statistical information available in /PIARC, 1999/ has been used as a basis for determining the initial frequencies for the scenarios involving the passenger cars and the HGV (see table 4.3.4.1). A value that seems reasonable to the author has been chosen. These values are based on a number of observations that have been carried out in various tunnels throughout Europe. It is of interest to get a value for the expected frequency of the number of accidents that lead to a fire per year.

Statistical information available for highways (Autobahn) in Germany has been used to determine the initial frequencies for each scenario involving hazardous goods transportation in tunnels. The procedure that has been used in this paper is based on the VTI model from the VTI report 387:3 Vägtransporter med Farligt Gods- farligt gods I vägtrafik olyckor (Road Transport Involving Hazardous Goods –Hazardous Goods in Road accidents) /Räddningsverket, 1996/. This is a model that is used to determine the expected number of hazardous goods accidents that result in a spill and could thus lead to hazardous conditions in the tunnel. The calculations are found in Appendix B and the results are illustrated in table 4.3.4.1 below. The initial frequency for the passenger car and the HGV is the frequency of fire occurring per year (see Appendix C) while for the hazardous goods transport (Gasoline and Propane) the value represents the frequency for hazardous goods transport accidents resulting in spills containing these substances per year. For the TNT scenario a spill will be equivalent of a detonation.

Scenario	Initial Frequencies (per year in the tunnel)
Passenger Car	$7,2 \cdot 10^{-7}$
HGV	$2,9 \cdot 10^{-6}$
Gasoline Transport	$1,4 \cdot 10^{-7}$
Propane Transport	$1,4 \cdot 10^{-7}$
TNT (explosive) Transport	$1,4 \cdot 10^{-7}$

Table 4.3.4.1- Initial frequencies

4.3.5 Event Trees

A simple event tree has been constructed for the relevant scenarios, to be able to determine the end scenarios for each initial scenario (see Appendix D). When assigning the frequencies to the different branches in the event tree certain assumptions have been made. In depth frequency studies should be performed when using this method in a real situation.

For the scenarios involving passenger cars and the HGV the initial scenario is an accident involving these vehicles. Thereafter the accident will either cause ignition or not, in the case where no ignition occurs it will be assumed that the people present in the tunnel will not be submitted to danger and thus no casualties will occur. The frequency of fire occurring in the case of a passenger car accident has already been calculated therefore no event tree will be constructed for this scenario. For the HGV scenario the effects of a functioning smoke ventilation system will be considered in the event tree.

Scenario	Frequency (per year)	Design Fire
HGV1	$1.26 \cdot 10^{-7}$	20 MW
HGV2	$1.40 \cdot 10^{-8}$	120 MW

Table 4.3.5.1- HGV Scenario Description

A separate event tree has been developed for each type of hazardous goods transport. A short explanation of the possible scenarios resulting from the event trees will follow.

For the accident involving gasoline the initial frequency has been calculated using the VTI model (see Appendix B) and represents an accident that has resulted in a spill. In constructing the event tree the following questions have been considered:

- To what size will the spill be limited?
- Will ignition occur?
- What are the possible outcomes?
- What is the worse case scenario?

The size of the spill has been divided into a small, medium and large spill, each resulting in different size pool fires. A scenario resulting in tank collapse has also been considered. Due to the gasoline being highly flammable and the presence of many ignition sources the probability for ignition will be high. A probability of 0.9 has been used for ignition to occur, this is similar to what has been used in similar projects /Rasmussen, 1994 / and seems reasonable to the author. The event tree results in 9 scenarios and the frequency for each scenario is found in table 4.3.5.1 below. For further information and an illustration of the event tree see Appendix D.

Scenario	Frequency	Design Fire
G1	$2.53 \cdot 10^{-8}$	300 MW
G2	$5.91 \cdot 10^{-8}$	17 MW
G3	$9{,}38 \cdot 10^{-9}$	-
G4	$1.39 \cdot 10^{-8}$	300 MW
G5	$1.39 \cdot 10^{-8}$	50 MW
G6	$3.10 \cdot 10^{-9}$	-
G7	$1.10 \cdot 10^{-8}$	200 MW
G8	$2.74 \cdot 10^{-9}$	170 MW
G9	$1.52 \cdot 10^{-9}$	-

Figure 4.3.5.2- Possible scenarios resulting from a gasoline spill

In the case of an accident with a transport containing propane the initial frequency has been calculated using the VTI model (Appendix B) and represents the frequency per year for an accident resulting in a spill. The event tree will initially distinguish between a continuous and a spontaneous release. The spontaneous release will either not ignite or ignite and cause either a vapor cloud explosion or a flash fire. The continuous release will not ignite, ignite and cause a flash fire followed by a jet fire or ignite and cause a flash fire followed by a BLEVE (see Appendix G for a brief explanation of these phenomena). The event tree results in 6 different scenarios (see Appendix D).

Scenario	Frequency	Description
P1	$7.33 \cdot 10^{-9}$	Flash Fire/BLEVE
P2	$1.15 \cdot 10^{-7}$	Flash Fire/Jet Fire
P3	$1.36 \cdot 10^{-8}$	No Ignition
P4	$1.89 \cdot 10^{-9}$	Vapor Cloud Explosion
P5	$1.89 \cdot 10^{-9}$	Flash Fire
P6	$4.20 \cdot 10^{-10}$	No Ignition

Figure 4.3.5.3- Possible scenarios resulting from a propane spill

An accident involving a transport of TNT (explosives) will either lead to a detonation or not (see Appendix A), no further event tree has been developed for this scenario.

The event trees that have been constructed represent a simplification of a real scenario. To construct an event tree that is a closer representation of reality would require a great amount of resources and is thus beyond the scope of this paper.

5 Consequences on Humans/Identification of Risk zones

In order to determine what effect the different scenarios, where a design fire has been defined will have on the humans in the tunnel the effects of the following contributing factors have been considered.

- Heat
- High concentrations of carbon monoxide
- High concentrations of carbon dioxide
- Low concentrations of oxygen
- Direct radiant heat from the flames (for pool fires).

Due to the lack of information of the consequences resulting from a flash fire, vapor cloud explosion and a BLEVE certain conservative assumptions have been made. This is further developed in section 5.5. The consequences from a pressure wave resulting from a TNT explosion has also been considered.

There has been much research conducted in the field of inhalation toxicology /Purser, 1988/, and it can generally be said that there are two main parameters that should be considered when analysing the toxicological effects of substances on living beings, the concentration of the subject that is being analysed and the duration of the exposure. These parameters have been calculated for each scenario where a design fire has been defined.

It has been of interest to calculate a time until death occurs for the passengers in the tunnel as a result of inhaling a toxic dose of the toxicant. For this purpose the concept of Fractional Effective Dose (FED) has been used. FED considers the contribution of different toxicants to reach the required effect (in this case death), taking consideration to the concentration and the duration of the exposure. The Fractional Effective Dose of the different toxicants are then summed during the exposure time until the value 1,0 is reached. At this point the limit for what humans can tolerate has been reached.

In order to calculate the Fractional Effective Dose for the different factors above, the temperature and relevant concentrations have been calculated.

5.1 Temperature Calculations

Due to the many uncertainties in the analysis, fire spread calculations have been carried out in a simplified manner. In the initial calculations it has been assumed that the smoke will follow the wind flow in the tunnel. It will also be assumed that the smoke will be evenly distributed through the whole section of the tunnel downstream of the fire. This is a simplification that will lead to conservative results, as it is normal that some stratification occurs. Normally if there is a ventilation flow of 1m/s the smoke will initially form an upper layer followed by a homogenous mixture of smoke and air. A homogenous mixture can be predicted to form at approximately a distance that is 10-20 times the hydraulic diameter /Bergqvist, 2001/. The hydraulic diameter (D_h) is defined as follows:

$$D_h = \frac{4A}{P}$$

Where A (74.25 m^2) is the tunnels sectional area and P (2*7.5+2·9.9) is the perimeter. This results in a hydraulic diameter of 8.5. Thus this would mean that at a distance of 85-170 from the fire the mixture of air and smoke would be relatively homogenous.

Having made the above simplifications and assumptions the temperature of the smoke at a certain time can be calculated with the following equation /Bergqvist, 2001/.

$$T_g(t) = T_0 + \frac{0,7Q(t)}{\mu\rho_0 A c_p} \qquad \textbf{equation 5.1.1}$$

Where

T_0 = Initial temperature in the tunnel (°C).

u = Wind velocity in the tunnel (m/s) (assumed to be 1 m/s, would actually be negative with satisfactory ventilation).

ρ_0 = air density in the tunnel (kg/m^3)

c_p = 1 kJ/°C kg for air.

Q(t) = Heat of release rate from the design fire at a certain time (MW).

The temperature will descend with the distance x from the fire and time according to the following equation /Bergqvist, 2001/.

$$T_g(x,t) = T_0 + \left[T_{g,0}(\lambda) - T_0\right] e^{\frac{-hP_x}{\rho_0 \mu A c_p}} \qquad \textbf{equation 5.1.2}$$

Where

$\lambda = t - (x/u)$ is defined as the time delay for transporting the smoke a distance x with a ventilation flow of u.

h = the lumped heat loss coefficient for the tunnel surface = 0.03 kW/m^2°C.

P_x= Perimeter of tunnel (m).

The results have been used as an input variable for calculating the FED due to temperature.

5.2 Calculating the Smoke Concentrations

The carbon monoxide (CO), carbon dioxide (CO_2) and oxygen (O_2) concentrations can be calculated assuming that there exists a homogenous mixture of smoke and air in the tunnel. The following equations have been used /Bergqvist, 2001/,

$$X_{O_2}(t,x) = \left[X_\infty - \frac{Q(\tau) M_a \left(X_\infty \frac{M_{O_2}}{M_a} + r_0 \right)}{\Delta H M_{O_2} \rho_0 u A c_p} \right] * 100$$ **equation 5.2.1**

$$X_{CO_2}(t,x) = \left[\frac{Q(\tau)(1 + r_0)}{\Delta H \rho_0 u A c_p} \right] * 100$$ **equation 5.2.2**

$$X_{CO}(t,x) = \left[Y_{CO} \frac{M_a}{M_{CO}} \frac{Q(\tau)}{\Delta H \rho_0 u A c_p} \right] * 1e6$$ **equation 5.2.3**

Where
Q(τ) has been previously determined for each scenario and time period
Molecular mass of each gas;
M_{o2}=32, M_{CO}=28, M_a=29 grams/ mole.
r_0= Stochiometric heat coefficient.
Y_{CO}= Fraction CO per gram burnt fuel that is involved in the fire (0.01-0.05 g/g).
ΔH= Effective heat of release (30 MJ/kg fuel).

The concentrations have been used as an input variable for calculating the FED due to high CO and CO_2 concentrations as well as low O_2 concentrations.

5.3 Calculating the Fractional Effective Dose

Tests have shown that once humans have received a dose of a toxicant so that they can no longer maintain normal functions, deterioration is quick. Starting with signs similar to those of intoxication and followed by unconsciousness resulting in death if exposure continues. Since this analysis will not consider fire brigade or rescue service intervention it has been assumed that once incapacitation (unconsciousness) has been reached, the person will be considered dead. It should be recognized that this is a conservative assumption, since in most cases the rescue service will be present to assist in the evacuation procedure. When analysing the results this means that a person will be able to proceed with evacuation until the Fractional Incapacitating Dose (FID) reaches unity. FID values have been calculated for the different toxicants. For some toxicants lethal levels have been considered, meaning if these levels are reached immediate death would occur. The result have been presented in graphs in Appendix F, illustrating how far the people present in the tunnel will be able to walk before either FID or FLD reaches the value 1.

5.3.1 Carbon Monoxide

Carbon monoxide is one of the major narcotic gases in fires and believed to be one of the prime causes of incapacitation and deaths /Purser, 1988/. Carbon monoxide reacts with hemoglobin in the blood to form carboxyhemoglobin (COHb). COHb reduces the bloods ability to supply critical organs with oxygen, thus resulting in the narcotic effect. The amount of COHb formed depends on the concentration of CO, the duration that it is inhaled and how much is being inhaled; the level of COHb therefore increases as long as CO is being inhaled. The effect at different levels of COHb is very individual to each human being; factors that have shown to affect a person's ability to survive high values of COHb have been age and general heath. Generally children, old people and people with limited cardio functions are more sensitive and show symptoms at a lower concentration. Values of 30 % COHb are often used to predict when unconsciousness will occur and 50% COHb levels usually result in immediate death. Another observation that has been made is that once these critical levels are reached the effects leading to incapacitation or death comes very rapidly. People are therefore normally not warned that they are being exposed to critical conditions before it is too late.

The level of COHb can be calculated with the following formula.

$$\%COHb = \left(3{,}317 * 10^{-5}\right) X^{1{,}036} * RMV * t$$ **equation 5.3.1.1**

where
X= CO concentration (ppm)
RMV= Respiratory minute volume (L/min)
t= time (min)

The FID can thus be calculated using a value of 30% COHb and the FLD using 50% COHb with the following formula;

$$F_{CO} = \frac{K\left(X_{CO}{}^{1{,}036}\right)t}{D}$$ **equation 5.3.1.2**

where
D= %COHb at incapacitation (30%) or a death (50%)
X_{CO}= CO concentration (from equation 5.2.3)
K= $8{,}2925 \cdot 10^{-4}$ (for RMV=25 L/min (light activity)) used when calculating FID values and $1{,}99 \cdot 10^{-4}$ for FLD.
t= time (min)

5.3.2 Oxygen

Incapacitation and death resulting from lack of oxygen has been observed at levels of around 10% oxygen. A critical value of 9,6 % oxygen will be used in this analysis; once this value is reached a person will no longer be able to continue the evacuation process. As soon as the level of oxygen is lower than normal it will start to have an affect on humans. Therefore the FID can be calculated according to the following formula.

$$F_{O_2} = \frac{t}{e^{8,13-0,54(20,9-X_{O2})}}$$ **equation 5.3.2.1**

where
t= Exposure time (min)
X_{O2}= Oxygen concentration (from equation 5.2.1)

5.3.3 Carbon Dioxide

The main negative effect of carbon dioxide is that it causes hyperventilation. Therefore it increases the RMV and the intake of other toxic substances. At levels of 3 % the RMV has been shown to increase a factor 2 and at 5 % a factor 3. To compensate for the increased intake of other toxic substances the following formula has been derived.

$$VCO_2 = \frac{e^{0,1903*X_{CO2}+2,0004}}{7,1}$$ **equation 5.3.3.1**

This factor is then multiplied by the toxicants FED value, which increases as a result of the higher CO_2 level.

Carbon dioxide will also have direct toxic effects increasing in severity with increased concentrations and exposure times. Loss of consciousness is predicted to occur within 2 minutes at 10 % concentrations. The FID value for CO_2 can be calculated using the following formula.

$$F_{CO2} = \frac{t}{e^{(6,1623-0,5189*X_{CO2})}}$$ **equation 5.3.3.2**

where
t= Exposure time (min
X_{CO2}= Carbon dioxide concentration (from equation 5.2.2)

5.3.4 Heat

The exposure to heat can cause incapacitation or death to humans in three different ways; by causing hyperthermia, direct skin burns and/or burns on internal (respiratory) organs.

Hyperthermia is caused by an increase in body temperature and when a body temperature of 42.5°C is reached the consequences will be fatal unless treated immediately. Factors that play a crucial role in determining how long humans can be subjected to various temperatures include the following points:

- Level of activity.
- Humidity level of the air (higher humidity levels will increase the effects of hyperthermia).
- The heat flux that the person is being exposed to.
- Ventilation flow speed (Increased airspeed increases the likelihood of lethal effects).
- Level of protective clothing.

Skin burns occur when the temperature at a depth of 0.1 mm reaches 44.8°C. When escaping from a tunnel humans can be subjected to all three types of heat transfer; conducted heat by coming in direct contact with hot objects, convection from the hot gases and radiation form the flames or the hot gas layer. Experiments have shown that burns from an object having a temperature of 60°C will occur after approximately 10 s (and after 1s if the object has a temperature of 80°C). Humans have been shown to be able to withstand a radiant heat level of 2.5 kW/m^2, this value will be used as the upper level of what humans can withstand for a short period of time. At temperatures above approximately 120°C skin burns will occur due to convective heat transfer to unprotected skin. The values that have been stated above are approximate values and depend greatly on the factors mentioned /Purser, 1988/.

Burns on the respiratory organs can be viewed as a second stage effect, where the primary effect is always burns on the skin of the face. In this analysis the tenability criteria that have been defined for skin will be assumed to be adequate for burns on the respiratory system.

To calculate the accumulated effect of the heat a FID value has been calculated. The FID value considers the effect of hyperthermia and external skin burns. In calculating the FID value average humidity and protective clothing values have been used.

$$F_{HEAT} = \frac{t}{e^{(5.1849-0.0273T)}} \qquad \textbf{equation 5.3.4.1}$$

where
t= exposure time(min)
T= Temperature (°C)

The F_{HEAT} component will only be considered for temperature over 37°C, for temperatures below this the surrounding environment will have a cooling effect.

5.3.5 Interaction Between the Different Toxicants

In a fire situation people will, to various degrees, be exposed to all of the conditions as described in sections 5.3.1-5.3.4 above. Depending on the situation, the severity of the different effects will vary, and there is no question that the effects of the different toxicants combined will be more severe than each one would on its own. Exactly how the different effects interact with each other to cause incapacitation or death is however uncertain. Some connections between the different toxicants can however be made. In this analysis the combined effect of CO, CO_2 and O_2 ($\Sigma F_{CO}*V_{CO2}+\Sigma F_{O2}$) will be considered and compared with the values received for CO_2 (ΣF_{CO2}) and heat (ΣF_{HEAT}). The value that reaches unity first will be the value that determines how long the evacuation can progress.

5.4 Radiant Heat Flux from Flame

In the direct vicinity of the fire, the radiant heat from the flames will have influence on the people that are present in these areas. Equation 5.4.1 has been used to calculate the heat flux at a given distance from the pool fires /Engelhard, 1997/. Due to the fast development of the hydrocarbon fires these fires will develop and radiate critical levels at an early stage when the evacuation process has not been completed. The affect from radiant heat will not be considered for the car and HGV scenarios because these design fires develop at a slower rate and people will generally be able to escape the areas where critical radiation levels could develop.

$$q'' = \frac{F_s * m * \Delta H_c}{4\pi\ X^2} \qquad \textbf{Equation 5.4.1}$$

where

q'' = Heat flux (kW/m^2)

F_s =Fraction of the combustion heat radiated from the flame surface ≅.0.3

m = Burning rate (kg/s)= 0.055 $kg/(s\cdot m^2)$

ΔH_c = Net heat of combustion at the boiling point of gasoline = 43.7 MJ/kg

X = The distance from the source to the receiver (m)

The critical radiation value that a human can withstand depends on various factors as described in section 5.3.4. A value of 10 kW/m^2 has been used as the value for when humans will no longer survive the level of radiation, this corresponds to critical radiation values as discussed in /Purser, 1988/. The result from the different size pool fires is found in table 5.4.1 and, as well as the amount of casualties in each case. Figure 5.4.1 shows the radiant heat levels at different distances form the fire. These calculations have only been carried out for the scenario where the fractional incapacitating dose or fractional lethal dose did not reached unity. If the FED or FLD values reach unity it will in the first case be for the people that are closest to the fire, an excessive level of radiation will thus also affect these people, but will not be relevant.

Scenario	Distance from fire where $10kW/m^2$ is reached (m)	Number of casualties
Small pool fire	2.4	$(0.4\cdot 4.8) \approx 2$

Table 5.4.1-Number of casualties due to radiant heat.

5.5 TNT Explosion

As a result of an explosion of 1000 kg TNT a pressure wave will be initiated at the site of the explosion. A Swiss reference /Anet, 1998/ has been used to calculate the maximum overpressure at different distances from the explosion site. The effect of the pressure wave on humans has thereafter been calculated using a method from the TNO handbook /Merx, 1992/.
The methodology used is described in Appendix A. Using the described methodology results in a total of 324 casualties.

5.6 BLEVE/Vapor Cloud Explosion/Flash Fire

For a short description of these phenomena see Appendix G.

A study has been undertaken to review how the consequences of the phenomena BLEVE, VCE and Flash Fire in a tunnel are treated. It can generally be said that there is no method of doing so. There is still a great amount of research that should be carried out in order to calculate the affects of these phenomena. One can adopt a crude method that is used for calculating the effects of these phenomena in the open and somehow try to adjust them to a tunnel situation, but there are a great number of uncertainties about doing this.

- Will there be sufficient amount of oxygen to create a BLEVE in a confined area such as a tunnel?
- Will the effect (pressure, radiant heat) increase due to reflection from the tunnel walls or vice versa?
- Will the BLEVE propagate throughout the tunnel or will the effect “die out”?

Commonly when analysing the consequences a conservative approach has been adopted. Due to the fact that the frequencies for these events are relatively low, it is often assumed that lethality is 100% in the tunnel if any of these phenomena occur.

These three phenomena should however be treated in different ways. When looking at the severity of the consequences caused one could rank the phenomena from BLEVE resulting in the most severe consequences followed by a VCE and then a flash fire. However it is questionable which phenomena will cause the most severe effects on humans. Without a doubt if a BLEVE does occur this will cause the most severe consequences to the humans that are left in the tunnel at the time of the BLEVE. For a VCE the time delay from that of the accident occurring to the ignition of a VCE or flash fire can be very short, normal ignition delay will most probably be between 1-5 minutes /Berg, 1997/, not giving the passengers time to evacuate, thus a larger amount of the humans in the tunnel are likely to be effected. However the time needed for a BLEVE to occur is usually considerably longer. By using Equation 5.5.1 that is used to calculate the thermal radiation pulse from a fireball resulting from a BLEVE in the open, the result shows that given a total of 10000 kg propane the radiation impulse at a distance of 500 m from the BLEVE will be approximately 4 kW/m^2. This gives an idea of the radiation levels that will be created in the open and a suggestion of the potential effects that might be created in a tunnel even though there are a great amount of uncertainties as mentioned above. There will also be a substantial effect from the overpressure that is created /Zalosh, 1988/.

$$q_{r\max} = \frac{(828\ m^{0.771})}{R^2} \qquad \textbf{Equation 5.5.1}$$

where
q_{rmax}= Peak thermal radiation (kW/m^2).
R= Distance that is to be investigated (m).
m= Mass of the fuel in the vessel (kg).'

Therefore in this analysis the conservative assumption has been made that there will be 100% casualty in the tunnel in the case of a BLEVE or VCE however different time delays have been considered. A time delay of 2.5 minutes will be used for the VCE scenario and a time delay of 10 minutes will be used for the BLEVE scenario. As a result no one in the VCE scenario will have time to complete evacuation resulting in 362 casualties. If a 10-minute time delay is assumed for the BLEVE scenario this will result in 197 casualties (see table 6.2.2.2).

For people who are present inside a cloud when a flash fire occurs the burns will be so severe that they will most likely result in death /Van den Bosch, 1992/. The size of the gas cloud will obviously depend on many different factors. However if the ventilation in the tunnel does not fail the cloud should form down stream of the accident and would therefore not affect the people in the tunnel directly. It has been assumed that a potential cloud could stretch from the accident site to a maximum of 150 meters in the direction where people are present, before ignition occurs. This is based on the assumption that an ignition of the cloud will most likely occur within 2.5 minutes after the accident resulting in a spill has occurred and that the gas cloud will most like not move at a speed greater than 1m/s. Finally the assumption has been made that there will be 100 % casualty inside the cloud. As a result of the above assumptions there will be 100 % casualty in zone 1, thus resulting in 121 casualties. The scenario that is initially a flash fire, followed by a jet will have the same amount of casualties as for the flash fire, this since the jet fire will not stretch and effect people in a greater distance than 150 meters from the fire, which has been assumed to be the area of the initial flash fire.

6 Evacuation Possibilities from a Tunnel

The problem of predicting how people will react in the case of an emergency situation in a tunnel is one that is not easily answered or one that can be treated with a general answer. How people react depends on various factors, depending both on the surrounding environment and the individual. Research has been carried out on predicting human behavior, and even though it is hard to predict how an individual will react in a certain situation, some factors that will influence how the person will respond have been identified. Marsden has identified six points /Marsden, 1999/.

- *Behavior is normally defined by the setting in which it occurs*

That is to say that an individual may react different in different tunnels, for example if the individual is aware of that the tunnel is under sea he or she will react different from being in a tunnel going through a mountain.

- *Human beings actively interpret their surroundings*

People interpret their surroundings and act upon their interpretation. People in general do not act mechanically in such a way as to run away when they smell or see smoke. On the contrary people will move through hazardous areas in order to escape via a route that is most familiar.

- *Role related rules guide the behavior of people*

It is essential that this is understood by the tunnel operators. It is important that people with leading roles or roles that can influence people in a positive way in the event of an evacuation are aware of their leading role and use it in the best way possible. Education of tunnel operators and staff is therefore a critical part of the total safety of the tunnel, it has to be expected that tunnel staff will act as leading roles whenever possible in a tunnel evacuation.

- *Peoples behavior is action oriented*

If a person is travelling through a tunnel there is always an action-oriented reason for doing so. The reason will contribute to how the person reacts. Due to this factor it is questionable if how people react in organised evacuation exercises are representative of how people will react in an emergency situation.

- *In an emergency situation flight behavior usually takes place*

People in an emergency will react in a way that seems logical at the time, but would under normal circumstances seem highly illogical. Examples are that people will do anything to reach their predestined escape route even if this means pushing other people out of the way.

These point stress the importance of performing an analysis of the evacuation situation for each specific tunnel.

6.1 The Evacuation Procedure

When discussing the evacuation process, that is the process from the time when people are posed with a threat until they are present in a safe place, it is normal to divide this into various segments. Each segment can thereafter be analysed and appropriate times can be assigned to each segment. The evacuation process will be divided into the following segments.

- Awareness time
- Reaction time
- Movement time

6.1.1 The Awareness time

The awareness time can be defined as the time taken for an individual to become aware of the threat. In a tunnel this obviously depends on what type of alarm system the tunnel is equipped with. How do people become aware of that there is a threat in the tunnel? This is a question that requires thought from all parties involved in a tunnel project. It is of great importance that the tunnel staff are sure on their actions in the case of an accident.
This time also depends on the severity of the accident. People in the direct vicinity of the accident will become aware through physical signs such as smoke or flames. Consequently this time will generally decrease when the severity of the accident increases.

People driving in a tunnel will thus either become aware of a threatening situation directly ie through physical signs or indirectly through some sort of alarm system ie warning on the radio. People that become aware of the threatening situation directly will most likely have a shorter awareness time than people who are warned indirectly. There are many factors that can play a part in whether a person becomes aware of the indirect warning. For example, people not listening to their radio may only become aware of a threatening situation through other people in the tunnel and the awareness time for these people will thus be noticeably longer. Tunnels should therefore be equipped with clear warning signs that are easily noticeable.

Thus awareness times are very individual and highly depend on the circumstances in the tunnel at the time of the accident. When assigning awareness times to individuals in an evacuation model it is therefore important to take this into consideration.

6.1.2 The Reaction Time

The reaction time is the time taken for an individual, once he has realised that there is a potential threat, to make an action, normally to make the decision to start evacuating. So the individual is aware of the threat but has an option of what to do. This is a factor that will extend the reaction time. It can generally be said that if the individual has only one option and this option involves following people the reaction time will be relatively short. Even though reaction times will vary considerably depending on the individual, there are certain factors that influence the reaction time. These include: people in the surroundings, the individuals' awareness of the situation, the surrounding environment (presence of warning signs, exit signs, etc.). These are all factor that will determine how long it will take the individual to come to a decision to evacuate one way or the other.

6.1.3 The Movement Time

This is the segment were evacuation models are a helpful tool. To calculate where potential bottlenecks will arise and queuing will occur. To determine the actual moving (walking) speed there are certain factors that have to be taken into consideration, these are: people density (amount of people per sq. meter), visibility conditions (reduced sight as a result of smoke? Location of emergency lighting?), slowest person determines actual speed (handicapped), ground conditions. The initial part of this segment deals with the time taken for the individual to evacuate the vehicle they are in. This time will greatly depend on the type of vehicle. To evacuate a car will only take a fraction of the time it takes to evacuate for example a double-decker bus. In the later it will also depend on the situation in the bus, if people are for example sleeping or awake. These are factors that are hard to foresee when modeling evacuation.

The variations in walking/evacuation speeds from a road tunnel could potentially be large depending on the factors mentioned above. The walking speed of people evacuating a tunnel will be assumed as being the same as people evacuating a transit station. Thus a walking speed of 0.7 m/s will be used /NFPA 130/. This will be considered as an average walking speed in situations where people can move freely and are not moving in crowds. This corresponds with the values of 0.5 –1.5 m/s as suggested in /PIARC, 1999/.

6.2 Modelling Evacuation

The factors mentioned above obviously pose a great difficulty when modelling the evacuation procedure. How should these factors be taken into consideration in order to get the most realistic evacuation model, when every individual will react different? The answer to this question is most likely that all the factors are not considered individually. Simplifications are necessary to get a model that is useable. Thus it is necessary to be aware of the simplifications and assumptions that are built in to a certain model. Many evacuation models have been designed to help tunnel designers and constructors to identify problems and optimise the evacuation strategies when designing new tunnels.

For the purpose of calculating the time required for people to complete evacuation from a tunnel a simple model has been used. The model is based on hand calculations and predetermined premovement times. Hand calculations determine the flow capacities of the available exits as well as potential queuing times. The model that has been used includes a simple vehicle queue model to determine the amount of people involved in the evacuation procedure.

6.2.1 A Simple Queue Model

The main purpose of the following queue model is to identify the amount of people that need to evacuate in the different scenarios. A critical part of the queue model is at what time period following the accident leading to a fire the warning systems will activate. This plays a crucial role in how many vehicles will come in direct contact with the threat of the fire. The detection time depends on the accident scenario as well as available systems for stopping vehicles from entering the tunnel.

In the direct vicinity behind the accident an initial cue will form. It has been assumed that the vehicles in front of the accident will continue safely through the tunnel and will thus not be affected by the accident. Depending on the time of detection and the position of the warning signs, queues, varying in size form at various distances upstream of the accident. As described in section 2.7, once an accident has been detected the warning signs will be activated, that is the signs will be changed to a red light and red crosses. Thus the individuals in the vehicles will become aware of the situation. Initially it is not sure that the vehicles will stop at the first warning sign, thus a time delay has been incorporated in the model. The vehicles that initially do not stop at the warning signs will thus join the end of the next queue.

Using the traffic flow information, and assuming that each car has an average of three passengers, mini vans an average of five passengers, buses an average of 20 passengers and trucks an average of 1 passenger, the population in the tunnel has been calculated. The calculations are shown in Appendix E.

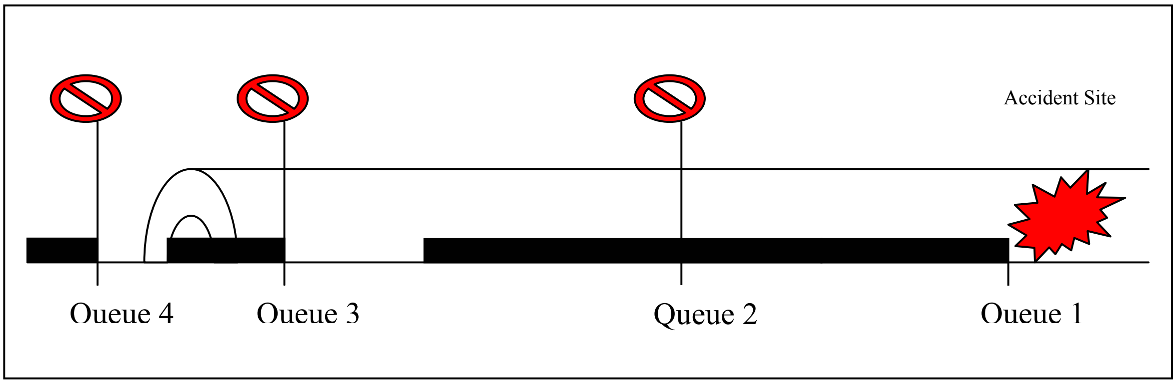

Figure 6.2.1.1- Illustration of the queue model

Using this simple queue model results in a total of 362 people having to evacuate the tunnel.

6.2.2 Evacuation Times

It is of interest to calculate the evacuation time in order to predict how many people will be affected by hazardous conditions at certain time points after the accident. It should be stressed that the evacuation times received are only indicative and should be used by decision makers as a tool to identify potential problems.

It is very difficult to assign a predetermined pre movement time to the evacuating people, as this time will vary greatly as discussed above. This is however necessary in order to get an idea of what will happen in the different scenarios. The premovement times that have been used in this analysis are values that seem reasonable to the author. Single point estimates of the premovement times have been used for simplicities sake. To see the effect of varying premovement times distributions of the premovement times can be used in the analysis, this has however been outside the scope of this report. The premovement times will depend on the location of the vehicle with respect to the accident. The closer the accident the more noticeable the sign will be, hence people will respond to the situation faster resulting in a lower awareness time. The awareness times in the tunnel will be divided into three zones. Zone 1 will start at the accident and extend 150 meters down the queue, in zone 1 the awareness time has been assumed to be 2 minutes. Zone 2 will span from 150 to 250 meters down the queue, here the awareness time will be 3 minutes. The final zone will extend from 250 meters to the opening of the tunnel, the people in this zone will have an awareness time of 4 minutes. The variation of the reaction time will be opposite that of the awareness time, that is the longest reaction time will be closest to the accident and the shortest will be in zone 3 see table 6.2.2.1. The reasoning behind this is that the escaping people will influence people in the vehicles and make them surer of their actions. Since in the area where the awareness time is shorter the people in the vehicles have less time to consider the situation, they will require longer time to make them sure of their actions, while in the remote zones people will have time to consider their actions before they have become aware of the situation and will therefore come to a decision quicker, making the reaction time shorter.

The next step in the evacuation procedure is for the people to evacuate their vehicles. The actual time taken to evacuate a car or an HGV will be considered as negligible, however due to the amount of people in a bus, this time is significant and has to be considered.

This time will be based on the flow capacity of a normal bus door (ex 1 person per 4 seconds). A value of 49 people per minute and available meter exit width will be used; this represents a crushed crowd condition /SFPE, 1996/, which seems reasonable to use on a bus where people are aware of the threatening situation and might start to act in an illogical manner. It has been assumed that the available exit width for the passengers on a bus is 0.8 meters. Thus the time taken for 20 passengers to evacuate the bus will be (20 people/(49·0.8)) approximately 30 seconds.

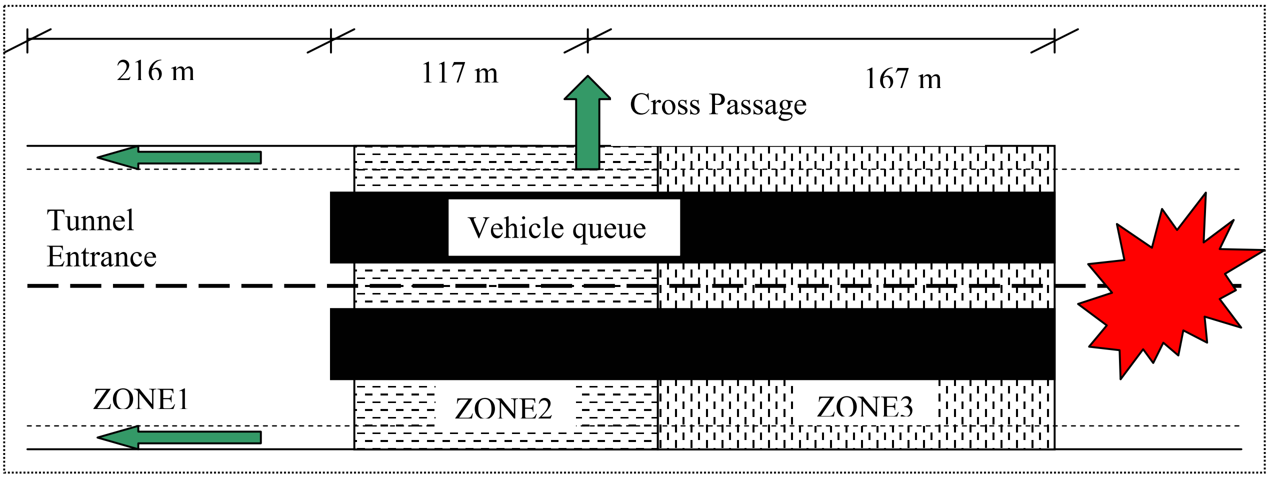

Figure 6.2.2.1 – Illustration of the situation in the tunnel.

After the people have evacuated their vehicles they will have an option of which way to evacuate the tunnel. As is shown in figure 6.2.2.1 the people can evacuate either through the entrance of the tunnel or through the cross passage to the other tunnel. It will be assumed that the people will have no difficulties walking through the existing vehicle queue to gain access to the cross passage. It is very difficult to predict which exit the people will use. It does however seem reasonable to predict that more people from zone 1 will use the cross passage exit since this is the closest exit and has to be passed in order to use the other available exit. On the other hand once the people in zone 3 have decided which way to evacuate they will only have one option in which exit to use, unless they change direction. Therefore it will be assumed that a greater percentage of the people in zone 3 will use the tunnel entrance as an exit. The flow capacity of the existing cross passage has been calculated. The cross passage has a width of 4.7 meters and a height of 3.9 meters. In the middle of the cross passage a door separates the two tunnel tubes. The width of the door is 1.2 meters, using information from SFPE handbook /SFPE, 1996/ the flow capacity of the door has been calculated. A value of 56 people per minute and meter available door width has been chosen; this represents a value for moderate crowd conditions.

Information regarding the assumed conditions for the people has been summarised in table 6.2.2.1. The calculations are based on that the 362 people in the queue are equally distributed, resulting in 121 people per zone.

Area	Awareness time (min) (+3 minutes delay for the queue to form)	Reaction Time (min)	% using each exit (number of people)		Max walking distance to cross passage exit (m)	Max movement time to cross passage exit using a walking speed of 0.7 m/s (sec.)
			Cross Passage	Tunnel entrance		
Zone 1	2	1.5	90 (109)	10 (12)	167	239
Zone 2	3	1	50 (61)	50 (61)	83	119
Zone 3	4	0.5	20 (24)	80 (97)	129	184

Table 6.2.2.1 – Evacuation information.

Table 6.2.2.1 shows that there is a total of 194 people that will use the cross passage as an exit, with the assumed flow capacity this would require 173 seconds. Therefore this time will not be a limiting factor and will not be considered further. The amount of people present in the tunnel and therefore affected by the fire at 30-second intervals has been calculated for people initiating from different zones.

The flow capacity of the emergency walkways has to be considered. Using a value of 59 people per minute /SFPE, 1996/ and available walkway width the flow capacity of the walkway will be approximately 1.2 people per second. This value is greater than will be achieved with people having a walking speed of 0.7 m/s. It will thus be the walking speed of the people that will be the limiting factor. It will be assumed that there is a gap of 1.4 meters between each person. People will thus start leaving zone 1 with a rate of 0.5 people per second. However the worse case scenario will be considered: that is the scenario when a bus is the first vehicle in the queue, this would theoretically mean that the last person would leave zone one after (180 s queue forming time+210 s. pre-movement time + 30 s. queuing time in bus + (167 m/ (0.7 m/s))) approximately 11 minutes (659 seconds). To compensate for this it will be assumed that after 600 seconds the only people left in zone 1 will be people from the first vehicle (bus). Thus after 600 seconds people will be leaving zone 1 at a rate of 0.3 people per second.

People leaving zone 1 through the cross passage will walk through 17 meters of zone 2 before entering the cross passage. This means that during the time people are evacuating zone 1 there will be an additional (17 m/(1.4 m/person)) 12 people in zone 2 for the time period up to 420 seconds. After 420 seconds there will be an additional 2 people in zone 2. To compensate for the people walking through zone 2 to evacuate through the tunnel entrance, an additional 8 people will be added to zone 2 for a time period of 150 (390 s) seconds after the people have started moving.

Theoretically the last person to leave zone 2 would be the last person leaving a bus that is located 83 meters from the cross passage. Thus the last person, starting out from zone 2, will leave zone 2 after (180 s queue forming time+240 s. pre-movement time + 30 s. time to evacuate bus + 119 s movement) approximately 9.5 minutes. It has been assumed that half the people from zone 2 will use the cross passage and half will use the tunnel entrance. It is therefore reasonable to assume that people will leave this zone at a rate of 1 person per second (double that of zone 1). The same procedure as for zone 1 will be used to compensate for the worst-case scenario with a bus and after 510 seconds people will start leaving the zone with a rate of 0.5 people per second.

Zone three extends all the way to the entrance of the tunnel. People from zones 1 and 2 will thus pass through zone 3. Half the people leaving zone 2 will pass through zone 3 and it will take a person approximately (250 m/ (0.7 m/s)) 6 minutes to pass through zone 3. Thus the amount of people travelling through zone 3 will accumulate. It will take the first people approximately 5 minutes to reach the tunnel entrance. The first people will hence reach the entrance after approximately 750 seconds. After this time it will be assumed that people leave zone 3 at a constant rate of 1 person per second. However it will be assumed that the people leaving zone 3 through the cross passage (24 people) will leave at a rate of 0.5 people per second. Consequently these people will have left zone 3 after 510 seconds.

Time after fire ignition (seconds)	People remaining in tunnel		
	Zone 1	Zone 2	Zone 3
390	121	121	121
420	106	121+8+12	121
450	91	91+8+12	121+15
480	76	61+8+12	106+30
510	61	31+8+12	97+45
540	46	16+8+12	97+60+8
570	31	1+8+12	97+60+12
600	16	0+12	169
630	7	0+2	169
660	0	0	169
690	0	0	169
720	0	0	169
750	0	0	169
780	0	0	139
810	0	0	109
840	0	0	79
870	0	0	49
900	0	0	19
930	0	0	0

Table 6.2.2.2 – People remaining in different zones.

7 Results/Societal Risks/ F/N Curves

The frequency for each scenario has been calculated as well as the consequence measured in number of casualties. The final societal risk has been displayed using a F/N curve. The scenarios have been combined and the result has been present in a total F/N curve as seen in figure 7.1. Using a F/N curve is a common way to describe the societal risk, which is a measure of the risk that the tunnel exerts on the society that is present in the tunnel. F/N curves illustrate the relationship between accident frequency and accident severity.

The number of casualties for each scenario that has been analysed as well as the frequency per year for each scenario is found in table 7.1. For each scenario the number of casualties has been determined. When determining the number of casualties for each scenario no consideration has been taken to people that might be trapped in their vehicle, consideration has only been taken to people that are able to start the evacuation process. This is a reason for there being no casualties in the car and HGV scenarios. As stated previously the results should be interpreted carefully.

Scenario	Frequency (per year)	Expected number of Casualties
Car	$7.20 *10^{-7}$	0
HGV1	$1.26 *10^{-7}$	0
HGV2	$1.40*10^{-8}$	0
Small Pool Fire	$5.91*10^{-8}$	2
Medium Pool Fire	$1.39*10^{-8}$	124
Large Pool Fire	$2.74*10^{-9}$	339
Tank Collapse	$5.02*10^{-8}$	362
Flash Fire/ BLEVE	$7.33*10^{-9}$	197
Flash Fire/Jet Fire	$1.15*10^{-7}$	121
Vapor Cloud Explosion	$1.89*10^{-9}$	362
Flash Fire	$1.89*10^{-9}$	121
TNT Explosion	$1.40\cdot10^{-7}$	324

Table 7.1- Frequency and number of casualties for each scenario that has been analysed.

7.1 *Interpreting the results*

In order to interpret the risk from a QRA on has to be able to compare the result with given risk criteria or have the expertise necessary to interpret the results and somehow come to a conclusion if the level of risk is acceptable, unacceptable or acceptable given certain modifications or risk reducing procedures.

Since the risk criteria vary in different countries it is difficult to generalise and say if the results are acceptable or not acceptable. Today risk criteria exist in a number of countries (Holland, Great Britain, Hong Kong, New South Wales (Australia), Switzerland, Canada and Santa Barbara (USA)), in figure 7.1.1 the Dutch and Swiss risk criteria are illustrated /Davidsson, 1997/. Figure 7.1.1 shows that in some areas the F/N curve enters the unacceptable region. If this were to be the information that was to be displayed to the management of a tunnel project it would thus show that the project would not be acceptable from a risk viewpoint. Thus a further analysis would be required where the effects of certain safety systems would have to be considered (see section 8.1.1-8.1.3 for examples).

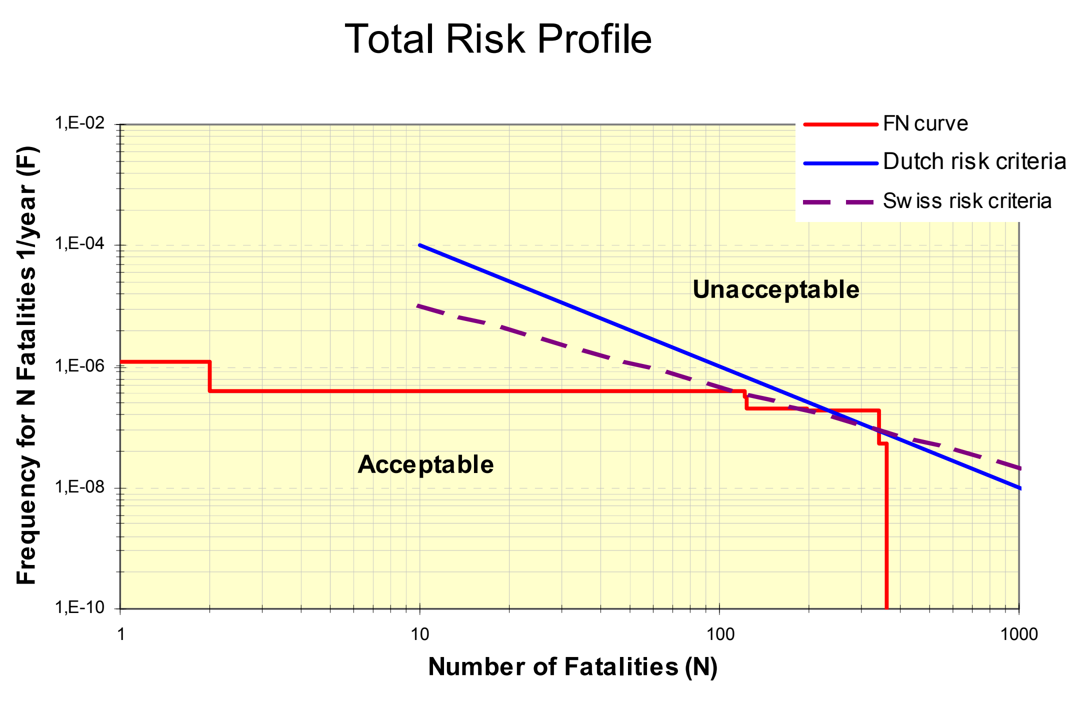

Figure 7.1.1- The total F/N curve for the scenarios that have been analysed.

8 Risk Reduction/Different Factors –How they Influence the Risk

In order to reduce the risk level in the model that has been used and described in this paper there are certain approaches, namely:

- **A**- Reduce the evacuation time,
- **B-** Prolong the time until hazardous conditions occur,
- **C-** Reduce the probability of an accident occurring.

The aim of installing various safety systems is therefore clear, to achieve one or several of the above-mentioned criteria. In this section different safety systems will be evaluated, to determine how they could potentially affect the two times that are relevant in the model that has been developed in this paper, time to complete evacuation (**A**) and time till hazardous conditions are reached (**B**). This is a procedure that needs to be developed for each separate tunnel project. A suggestion of how a ranking system can be designed, when evaluating different safety systems is also discussed.

There are of course safety systems that can be installed that will reduce the probability of an accident (**C**). This will not be considered in this paper because it is believed that the major precautions that have to be taken in order to reduce the probability of an accident occurring are not based on systems in the tunnel. Statistics show that human error is the main cause of accident in tunnels /Astra, 2000/. In order to handle this problem the following points should be brought to the attention of the decision makers.

- Need for some sort of program/ information campaign to increase the knowledge of drivers on how to react in case of an accident/fire in a tunnel. This could suitable be introduced in co-ordination with employment at a truck transport company or in the driving license attaining process.

- Clarification of special road rules for tunnels such as- no overtaking if there is only on lane, no reversing, always have lights on vehicle, no stopping in tunnels unless emergency and in that case turn off engine etc.

- How to react in the case of a fire in a tunnel- Keep distance, put out fire with hand held fire extinguishers available in vehicle or tunnel, alarm, warn and rescue other people in the tunnel. This should be a natural part of the theory that is taught when attaining a driving license, especially in countries where there is a large amount of tunnels.

8.1 Developing a Ranking System

In order to get an overview of the positive effects of a certain safety system it is of great help to develop some sort of ranking system. One approach when developing a ranking system is to analyse the two time components (**A**) and (**B**) as previously described, one being the effect on the evacuation time and the other the effect on the time until hazardous conditions are reached. A detailed analysis should be carried out on each relevant safety system, which should lead to each safety system being assigned a certain value. Each value should be assigned a time (an example given in table 8.1.1 below). The times used in each specific project should be based on the analysis that has been carried out. The idea behind this ranking system is to demonstrate a methodology that could be used to evaluate different safety system, and could be a good tool for decision makers when deciding upon which resources should be spent. In order to do this one has to additionally consider the economics (initial costs, maintenance cost, life length, etc.) associated with each safety system. This should also be the basis of a ranking value as described above. The result of this analysis should be that each safety system is assigned a value, for example between 1 and 5 where 1 is the best and 5 the worst, based on this the choice of which safety systems are relevant for a certain tunnel should be obvious.

A short description of the following safety systems will follow as well as the effects they could have on the end results when doing a QRA.

- Ventilation systems.
- Suppression systems.
- A well-established tunnel safety management system.

8.2 Ventilation System

When designing a ventilation system for a certain tunnel there are several parameters that have to be taken into consideration, these can be summarised in figure 8.2.1.

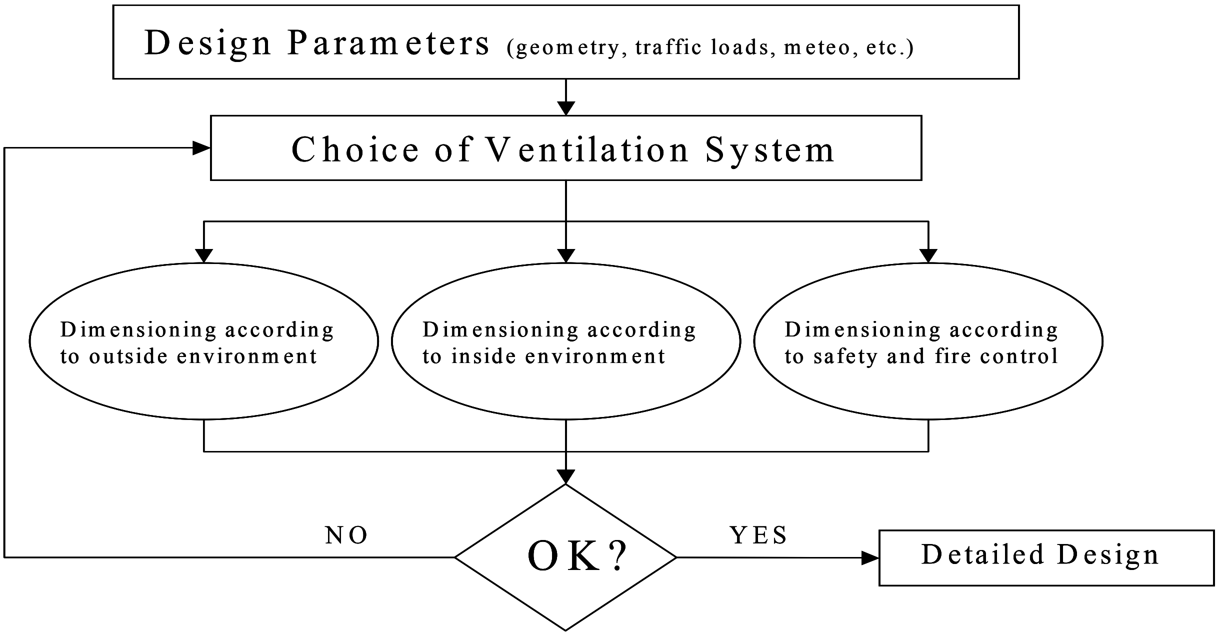

Figure 8.2.1 - Possible logical flow of the ventilation design /PIARC, 1999/.

The ventilation system has to be designed to keep tenable conditions in the tunnel during normal operation as well as in the case of fire. In the case of fire it is the forced ventilation that is to prevent the spread of a hazardous region to places from where people must evacuate. A study has been undertaken to analyse the effect of different ventilation speeds in tunnels and how this effects the time need for hazardous conditions to reach certain areas in a tunnel /Holmstedt, 1996/.

One can see that the ventilation speed is directly connected to the factor **B**. The higher the ventilation speed the longer it will take for hazardous conditions to arise in an area in the tunnel that is upstream of the fire site. The graph below shows the delay in the time until hazardous conditions are reached for various ventilation velocities.

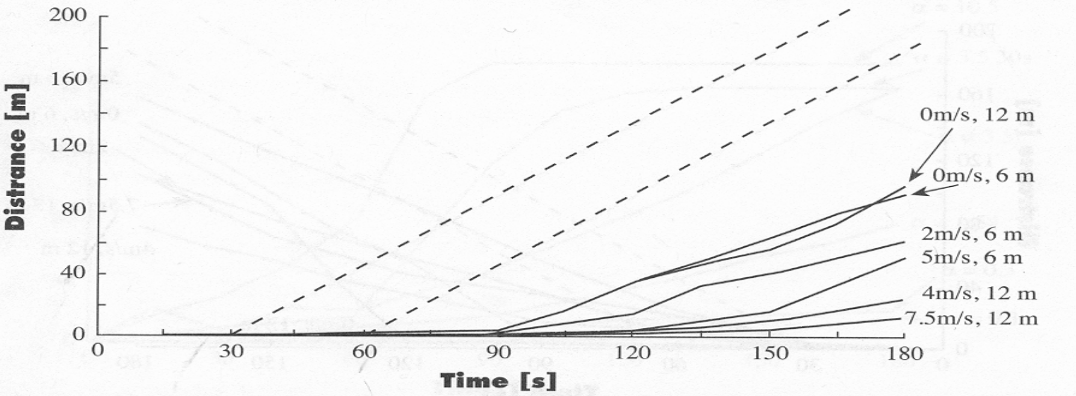

Figure 6. The influence of longitudinal ventilation on the spread of a hazardous region due to temperature in a tunnel for various wind speeds and a fire growth parameter of α=1.540 kW/s^2 in 6- and 12-m-wide tunnels. The dashed lines correspond to a walking speed of 90 m/min, starting at 30 and 60 s, respectively.

Figure 8.2.2 - /Holmstedt, 1996/.

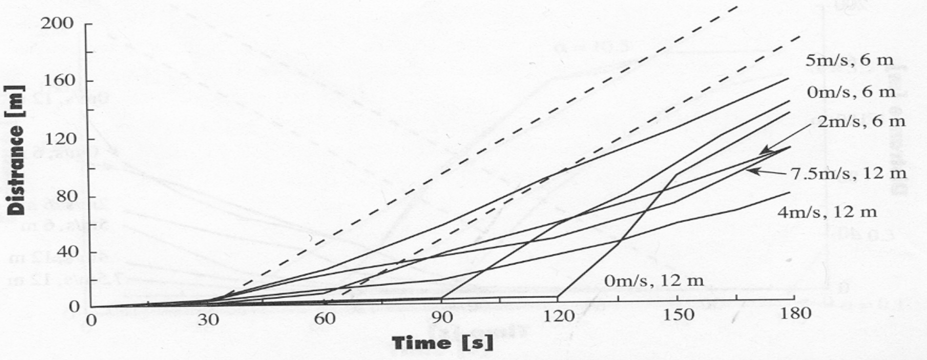

Figure 7. The influence of longitudinal ventilation on the spread of a hazardous smoke region in a tunnel for various wind speeds and a fire growth parameter of α=1.540 kW/s^2 in 6- and 12-m-wide tunnels. Dashed lines correspond to a walking speed of 90 m/min, starting at 30 s and 60 s, respectively.

Figure 8.2.3- /Holmstedt, 1996/.

The graphs above confirm that it is not the temperature that will have lethal effects on humans however it is the toxicants in the smoke. Figure 8.2.2 shows that with increased ventilation velocities the time until lethal temperature conditions are reached will be delayed. However as figure 8.2.3 shows this is not necessarily the case for toxic smoke. Figure 8.2.3 shows that the scenario with no ventilation may not initially be dangerous, this due to the stratification of the smoke in the ceiling of the tunnel, however when the smoke layer reaches below head height the situation will worsen dramatically. A solution to this problem would be to have a ventilation system with ventilation exhaust ducts that are spread throughout the tunnel, which is able to ventilate the smoke before it reaches a critical level in the tunnel. In order for this to work satisfactory this would require ventilation ducts every 100 meters /Holmstedt, 1996/.

Therefore one cannot make the conclusion that the situation for the evacuating people in a tunnel will improve with increased ventilation velocity. In stead the ventilation system should be designed in such a way as to remove the smoke from different areas in the tunnel via exhaust ducts.

8.3 Suppression System

Installation of a fixed fire suppression system in a road tunnel has both advantages and disadvantages. The advantages and disadvantages should be considered for each specific tunnel when considering the installation of a fixed fire suppression system. The following factors are important when considering the installation of a fixed fire suppression system:

- What type of system is appropriate (water spray, water mist, foam water)?
- What delivered water densities are required?
- What operating pressure is required?
- What types of fires are likely to occur in the tunnel that is being analyzed (flash point of the fuel that is being burnt)?

The disadvantages that are associated with the installation of a fixed fire suppression system include /Arvidson, 1999/:

- High costs.
- Reduced visibility during activation, making the evacuation process more difficult.
- Water spray systems could increase the size of a fire due to flammable liquids being carried on the water, spreading the fire and increasing its size.
- False activation could potentially cause accidents.

There have however been several test conducted which show the positive effects of a fixed suppression system /Arvidson, 1999/. Fires with a HRR of 100 MW have shown to be extinguishable within a short period of time if the system is designed correct. Therefore one of the main advantages is that an automatic suppression system will limit the size of a fire and not allow a fire to develop to a large inferno. As this analysis has shown it is the scenarios with large fast developing fires (hydrocarbon fires) that pose the greatest threats to humans in the case of a tunnel fire. If a fire could potentially be controlled by a suppression system and the HRR kept under a certain level, the amount of casualties could be reduced dramatically. In order to quantify the result from the installation of a fixed suppression system, one can analyse the maximum fire that could develop given a certain suppression system. This has not been conducted in this analysis; however if it is assumed that the maximum fire size given a suppression system would be equivalent of a “small” pool fire as opposed to a “large” pool fire, the result in number of saved lives is easily justified given the increased costs.

AFFF (foam-water) system has been used in Tunnels on the Betuweroute rail freight link between the Port of Rotterdam and the German border. 3/8 scale experiments showed that it was successful in extinguishing and protected against reignition. The AFFF system provided adequate protection for firemen to do their job in the case of a fire in a tunnel /Hauptmanns, 1990/.

8.4 Tunnel Safety Management System

A tunnel safety management system (SMS) should be an integrated part of the tunnel design process. By implementing an integrated SMS at an early stage in the design process of a tunnel project it enables a more structured and simple approach towards safety issues. When using a structured tunnel SMS it enables a proactive approach towards safety issues.

The tunnel SMS should be implemented throughout the organisation to get every level in the organisation involved in the safety issues that have to be treated. Initially the organisation should have a clear SMS policy, where the organisation clearly states the safety goals and an overview of the organisations view towards safety issues is defined.

The organisation should have a plan in how the issues and goals that are stated in the policy should be implemented. This plan should at least include areas of responsibility, dead lines by when certain goals should be reached and the resources that are available. A special group should be created to deal with the safety issues and to make sure that the safety projects are followed through. This group should suitably consist of a project manager and some sort of project group that includes representatives from all areas that are involved in the relevant issues.

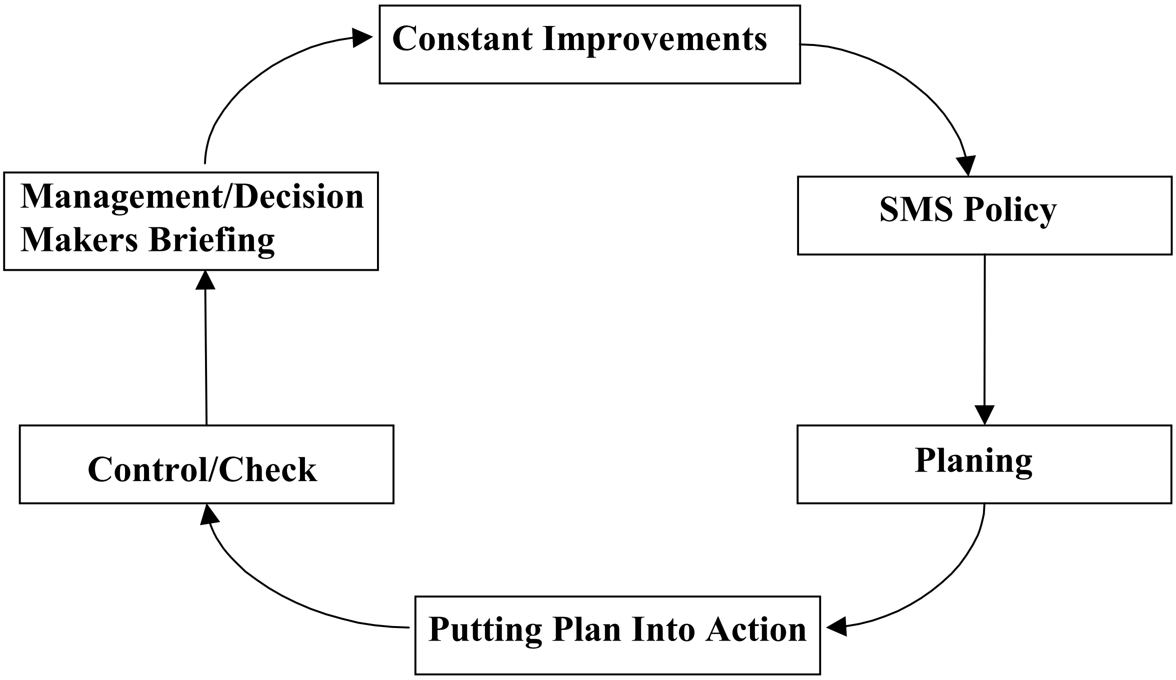

Figure 8.4.1 - Safety Management System Cycle /Kemikontoret, 1997/.

When putting the plans into action it is important that relevant information reaches every part of the organisation that is involved in the process. It is also important that the plan is carried out by competent personnel, that is to say that the person in charge for a specific area should have the required education enabling him/her to be confident in accomplishing the goals that have been set. It is therefore necessary that there are resources available to educate staff when this is necessary. The SMS should also include some sort of review system, both internal and external review is necessary to get a neutral perspective, and make sure that the system includes all necessary points.

There are many advantages of having a SMS in tunnel projects some that have been mentioned above. Other advantages include the following:

- The system helps the organisation to follow local and international safety rules and standards,
- It helps to increase the credibility of the organisation and show that the organisation prioritizes safety issues,
- Increases the effectiveness of the organisation when dealing with safety issues,
- Helps keep a good relation between the organisation and the public, since one of the main concerns of the public is safety.

It is hard to see the direct result in the form of a reduced amount of casualties in a QRA that a tunnel SMS would achieve. However having a systematic approach towards the safety issues will increase the tunnel personnel’s knowledge about the relevant issues. Examples of situations where this will be noticeable is in the daily work of the tunnel operating personnel’s routines, such as installing operating systems that are sufficiently robust as to allow for operator errors in high stress situations which might arise in the case of an accident. Part of a tunnel SMS could also involve regular fire and evacuation drills where the operating personnel get to practice their leading roles in the case of an emergency /Kemikontoret, 1997/.

8.4.1 Example

To illustrate how a tunnel SMS should be used and integrated into a tunnel organisation an example will be used. In the example some tunnel safety management system policies will be stated along with some examples of necessary routines.

Safety management systems policy should include the following points /Kemikontoret, 1997/,

- *Issues regarding safety in the tunnel are of top priority. These issues should always be considered in the organisations decision-making process and be a natural part of the organisations management.*
- *The management of the organisation has the primary responsibility for the safety issues in the tunnel.*
- *All members of the tunnel operational organisation have a personal responsibility for the safety issues associated with the operation of the tunnel.*
- *The tunnel organisation should at least abide to the local laws and regulations, the organisation should strive for having a higher level of safety then forced by the national/international legislation.*
- *All employees should have a high level of knowledge and engagement in safety related issues.*
- *The tunnel organisation should strive at utilising and installing the best possible safety systems and technology.*
- *The organisation should regularly go through and analyse the safety issues in order to prioritise where resources should be spent in order to constantly improve the level of safety in the tunnel.*
- *The organisation should work with the safety issues proactively, in order to reduce the risk and minimise the risk for the tunnel being out of use for a long period of time.*
- *Vehicle accident in the tunnel should always be reported and documented, reasons for the accident occurring should be analysed in order to reduce the probability of the same accident happening again.*

- *The issues of safety should be discussed openly within the tunnel organisation, the operators should learn from their mistakes.*

- *The organisation should regularly perform audits to make sure that the policies as stated above are followed.*

Based on the policy, routines for how the work is organised should be set up. Below are a few examples of some routines that should be followed in order to make sure that the organisation follows what has been defined in the tunnel safety management system. These **routines** should be detailed enough to fulfil what the policy states. Each routine should be clearly documented and should include the aim of the routine, the scope, the method and guidelines in the routine and who is responsible. Each routine should be documented with the headings as shown in table 8.4.1.1

Routine	
Aim	
Scope	
Method/Guidelines	
Responsibility	

Table 8.4.1.1-Headings in routine documentation

Below are some examples of areas where routines should be created,

- Permission for work to be carried out in the tunnel for external workers (ie installation/maintenance of tunnel safety systems)
- How should accidents/incidents be reported
- Healthcare of tunnel workers
- Education for tunnel staff
- Internal/external communication
- General rules of ordinance
- Transport of Hazardous goods
- Modification of existing safety systems

For every tunnel project a list of points should be made and documentation according to table 8.4.1.1 should be created.

A suggestion for a suitable routine for the transportation of hazardous goods is given below in table 8.4.1.2.

Routine	Controlling the transportation of hazardous goods transports through the tunnel
Aim	To make sure that the transport of hazardous goods through the tunnel takes place in an adequately safe manner.
Scope	The routine should be applied for all hazardous transports that used the tunnel
Method/Guidelines	• Before a hazardous transport enters the tunnel a representative from the tunnel staff should go through a check list with the chauffeur to make sure that all safety systems on the vehicle are functional. • Staff in the control room should have a check list of relevant safety measures depending on the substance and amount that is being transported. • Staff are responsible to make sure that the chauffeur is aware of how to act in an emergency situation • Emergency services should be contacted, prior the transport entering the tunnel, in cases where specially hazardous materials are being transported, making sure that they are aware how this substance should be treated in the case of an accident. • A “check-out” system should exist making sure that the tunnel staff is aware when the hazardous transport has left the tunnel, not more than one hazardous transport should be allowed inside the tunnel at a time.
Responsibility	There should always be a tunnel staff member that is responsible for making sure that all necessary precautions are made before the hazardous transport enters and leaves the tunnel. This responsibility should be associated with a certain task in the control room, and it should always be documented who is responsible at a given time.

Table 8.4.1.2- Routine for controlling the transport of hazardous goods through a tunnel, should be complemented with relevant technical check lists.

9 Conclusions and Suggestions on Further Work

The methodology that has been described in the following paper is a good starting point for further developing guidelines and routines for performing a QRA on a road tunnel. This paper presents a methodology that is appropriate to use in the initial stages of a tunnel project. It is a good tool to use in order to get an overview of the risk level in the tunnel. The results are a good basis to have when making further decisions on what safety systems are required to have an acceptable risk level in a certain tunnel.

If the results show that the risk-level is acceptable, when compared to a defined risk criteria it is a good signal that the tunnel does not present a greater threat than any other risk object in that specific society.

The methodology that is presented in this paper is a suggestion on an appropriate method when evaluating the risk levels in road tunnels, which is not to say that it is the only way of doing this. The most important issue is however that there exists some standard methodology when evaluating the safety in tunnels. It is believed that the suggested methodology is not too complicated or requires too many resources to be able to be carried out for every tunnel project. It is important that a bench marking study is carried out, especially in countries with many tunnels, using a standard methodology, this enables the decision-makers to get a feel for the risk level that is present and enables them to compare the risk levels in different types of tunnel solutions. In turn this helps in the process of increasing the safety in tunnels.

The suggested methodology does however need further development in the following areas in order to make the results trust worthier.

- Choosing relevant scenarios with assigned design fires.
- Determination of relevant frequencies, better statistical information is required
- Evacuation procedure, determination of relevant premovement times. How should premovement times be chosen?
- Some sort of standardised risk acceptance criteria.

These are all points that have to be further developed, and the more effort that is spent on developing these points the more accurate the actual risk estimations will become.

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Appendix A - The calculation of the propagation of a pressure wave resulting from the explosion (detonation) of the equivalence of 1000 kg TNT in a tunnel

The following method /Anet, 1998/ has been developed to determine the peak overpressure as a function of charge density in a tunnel. The peak pressure is determined form the figure A1 below. The input variables are,

W - Mass of explosive (kg)..1000 kg
A – Cross section area of the tunnel (m^2)................................75 m^2
L.-. Distance from explosive to point of interest (m)................varying

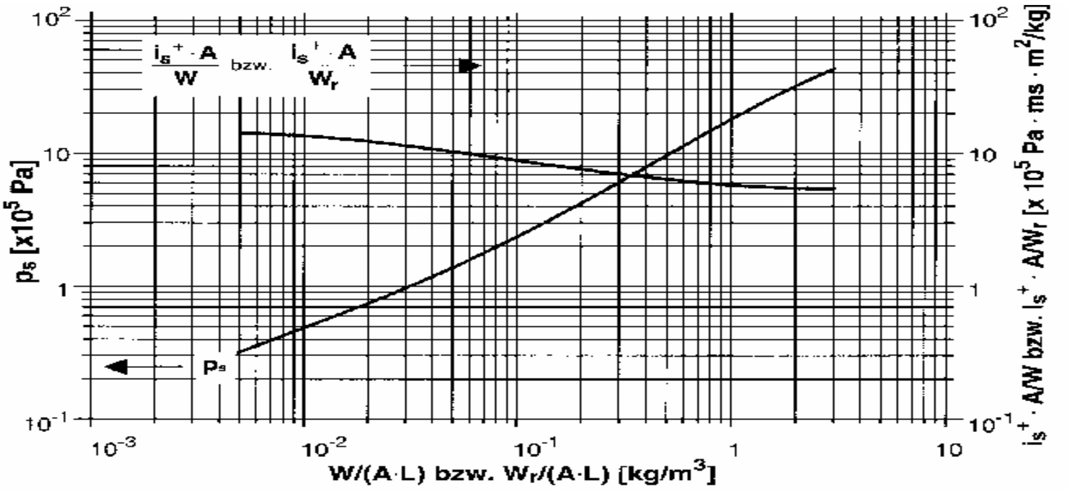
The charge density (CD) is defined as follows;

$$CD = \frac{W}{A*L}$$

The peak overpressure was determined at various distances (L) from the explosion site using figure A1.

L	**W/(A*L)**	**Peak Overpressure P_s ($*10^5$ Pa)**
50	$2.7*10^{-1}$	6.0
100	$1.3*10^{-1}$	3.5
150	$8.8*10^{-2}$	2.2
200	$6.7*10^{-2}$	1.8
250	$5.3*10^{-2}$	1.6
300	$4.4*10^{-2}$	1.4
350	$3.8*10^{-2}$	1.2
400	$3.3*10^{-2}$	1.0
450	$3.0*10^{-2}$	0.95
500	$2.7*10^{-2}$	0.90
550	$2.4*10^{-2}$	0.80

Table A1



Spitzenüberdruck p_s und statischer Impuls der Überdruckphase i_s^+ in Abhängigkeit der Ladungsdichte W/(A·L) bzw. W_r /(A·L).

Figure A1- Peak overpressure as a function of charge density (CD) /Anet B., 1998/

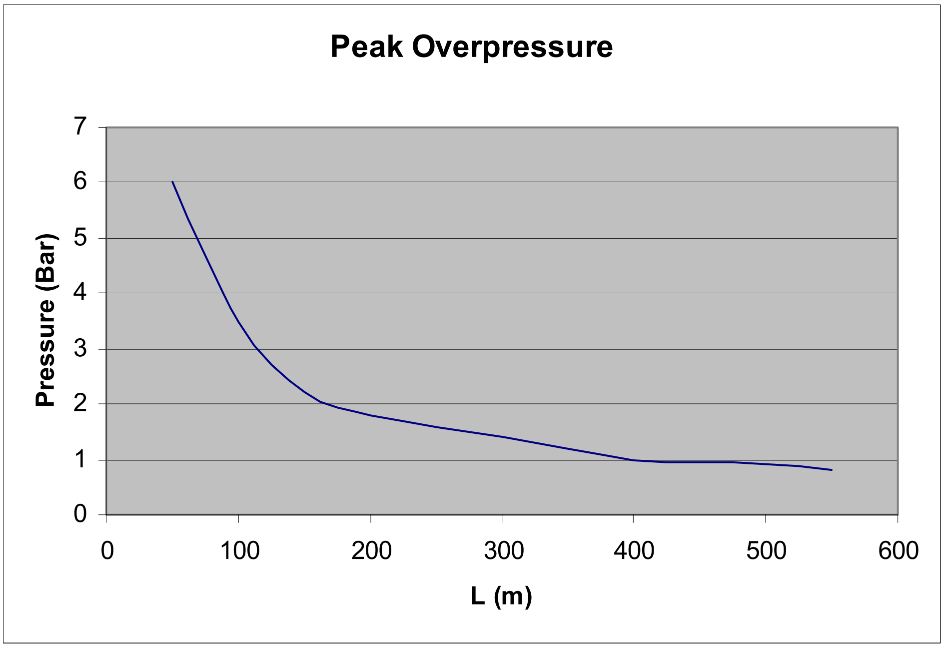


Figure A2- Peak overpressure at different distances from the explosion site

There are many different suggestions on what peak overpressures a human can withstand without causing lethal damage.

Richmond /Richmond, 1962/ shows the results of tests that have been performed on various animals that have been subjected to a range of shock pressures to determine their LD_{50} values (values that result in death for 50 % of the tested population). By plotting the animals average body weight against the observed LD_{50} values, the LD_{50} value for a 70 kg animal was extrapolated to approximately 55 psi ($3.79 \cdot 10^5$ Pa). Another study /Navy Publications, 1969/ reports a threshold for lethality at 100 psi ($6.9 \cdot 10^5$ Pa). The FOA Handbook /FOA, 1995/ uses a value of $2.6 \cdot 10^5$ Pa for 50 % lethality (LD_{50}).

To determine the effect on humans, information from /Merx, 1992/ has been used. It has been assumed that the duration time of the pressure wave at a certain point in the tunnel is constant and is equal to 0.04 seconds. With this information and information regarding the peak overpressure figures A3-A5 have been used to determine the probability of survival at different distances (L) from the explosion site.

The method that has been used will give approximate values of the probability of survival Due to the variety in the figures the effect zone of the pressure wave caused by and explosion will be divided into 2 different sections with different percentages of lethality 99% and 50 %.

The effects of a pressure wave on humans are usually divided into different categories /Merx, 1992/. Direct effects take consideration to the injury the pressure change can cause to the sensitive internal organs (usually the lungs), this is considered in figure A5 below where an average person weighing 70 kg has been considered. Secondary effects consider the consequences of fragments and debris hitting humans as a result of an explosion. These effects are difficult to predict and depend on the amount of objects located in the vicinity of the explosion. These effects have not been considered in the analysis. Tertiary effects consider the effect of whole body displacement and collisions with stationary objects. Tertiary effects are considered in figures A3 and A4 below (for a 70 kg person). The severity of the injury due to tertiary effects depends on the velocity of the impact, the shape and hardness of the object and on the part of the body that is involved in the impact.

Since the skull is the most vulnerable part of the body in the case of a collision, lethality due to a skull-based fracture will determine the length of the lethality zones (figure A3). The impulse of the pressure wave is the peak overpressure (P_S) multiplied by the duration time of the pressure wave (0.04 s).

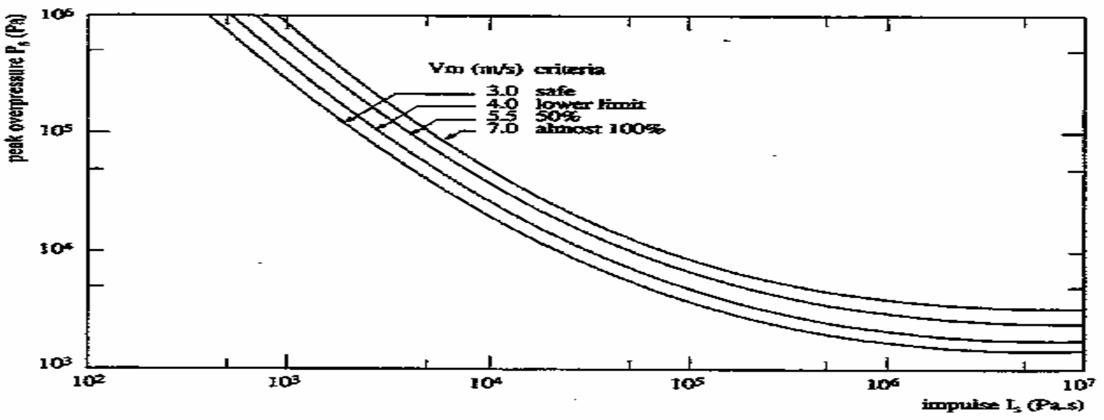


Fig. 10: P-I graph for a skull-base fracture.

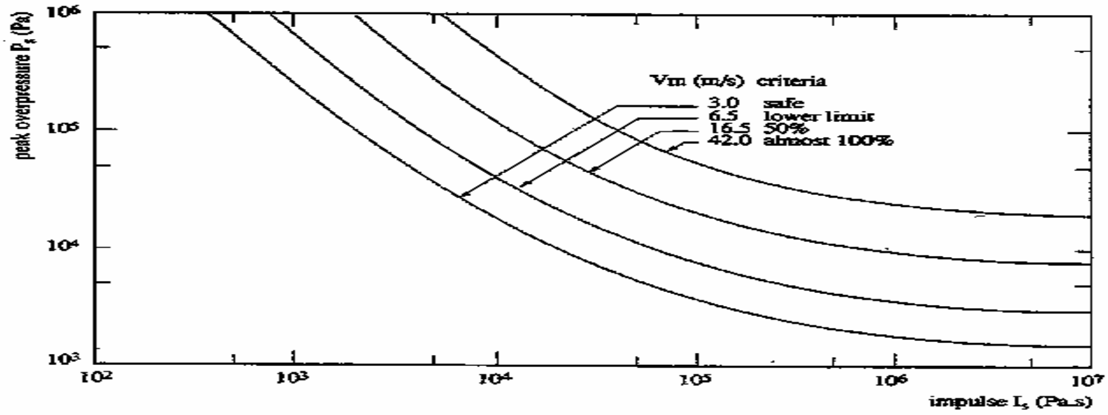


Fig. 11: P-I graph for impact of the whole body.

Figure A3 (top) A4 (bottom) /Merx, 1992/.

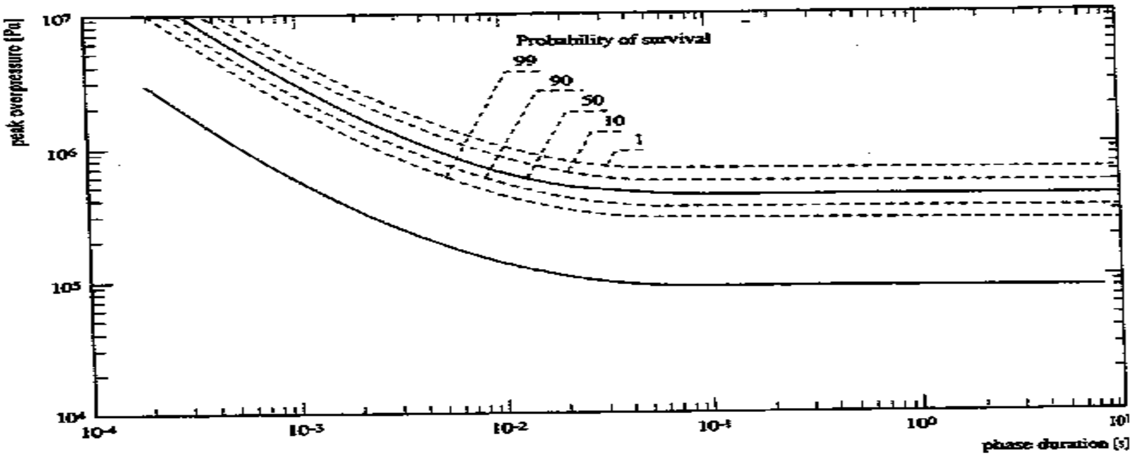


Fig. 3: Probability of survival in the case of lung damage for a person weighing 70 kg at 100 kPa atmospheric pressure [1].

Figure A5./Merx, 1992/

L	$I_s(\cdot 10^4 \mathrm{Pa}\cdot\mathrm{s})$	Lethality(%)
50	2.4	99
100	1.4	99
150	0.88	99
200	0.73	99
250	0.64	99
300	0.56	99
350	0.48	99
400	0.40	99
450	0.38	50
500	0.36	50
550	0.34	50

Table A2- Lethality zones

A conservative approach has been used since it is very uncertain what protective effect the vehicles will have. Therefore it has been assumed that there will be 99% casualty in an area up to 400 meters from the explosion site, thereafter there will be 50% casualty. It has also been assumed that the time delay until the explosion occurs is sufficient so that queuing will occur and the vehicles in front of the accident will have time to exit the tunnel safely.

As a result 99% of the people in zone 1 and 2 will die from the effects of a pressure wave from an explosion of 1000 kg TNT. Zone 3 extends 250 from the site of the explosion to the opening of the tunnel. It will be assumed that the people in the zone are evenly distributed. Therefore in 40% of zone 3 there will be 99% casualty and in the remaining of zone 3 (60%) there will be 50 % casualty. The total amount of casualties is:

$$\underbrace{0.99\cdot(121+121)}_{\textbf{Zone 1 \& 2}} + \underbrace{0{,}99(0.4\cdot 121)+0.5(0.6\cdot 121)}_{\textbf{Zone 3}} = 324 \text{ people}$$

Appendix B- Determining the Frequencies for Hazardous Goods Transport Accident - Using the VTI model

The VTI model /Räddningsverket, 1996/ has been used to determine the frequency for a hazardous goods transport. The in put data is taken from a calculation matrix in /Räddningsverket, 1996/. This matrix gives values for the following input data that are necessary to calculate the expected number of accidents involving hazardous goods; accident quotes, fraction of accidents involving single vehicles, and fraction of hazardous goods accidents resulting in spills.

The input data varies for different road types, speed limits and surrounding environment. For this analysis the following conditions have been chosen to represent the tunnel; countryside environment, speed limit of 90 km/h and a multilane highway. In the analysis the tunnel has been divided into one homogenous section with the same input data for the whole section. Another possible approach could be to divide the tunnel into sections with varying input data, some research has been done in the area of where accidents in tunnels occur most frequently and this could be a basis on assigning higher or lower accident quotes to different sections.

The fraction of hazardous goods transports is taken from /Ernst Basler, 2001/ and is based on the total amount of hazardous goods transport on motorways (BAB) in Germany 1995.

Input Data	*Variable*	**Value**
Vehicles per 24 hours	A	44300
Tunnel length (km)	L	1,1
Fraction Hazardous Good Transports	X	2,40E-03
Speed Limit (km/h)		80
Accident quote	B	4,00E-07
Fraction of accidents involving a single vehicle	Y	0,35
Fraction of Hazardous Goods accidents resulting in spills	C	0,22
Expected amount of accidents in the tunnel per year	O	7,11
Expected amount of accidents involving a single vehicle	D	2,49

Table B1 – Input data for the VTI model

The expected number of accidents in the tunnel per year is calculated with the following formula:

$$O = A * B * L * 365 \qquad \textbf{Equation B1}$$

The expected amount of accidents involving hazardous goods and resulting in a spill is calculated with the following formula:

$$F = O * C\left(\left(Y \cdot X\right) + \left(1 - Y\right)\left(2X - X^2\right)\right)$$ **Equation B2**

Uncertainty Analysis

In order to get a worthy final result, an uncertainty analysis has been carried out on the variables in table B2. The uncertainty analysis has been done with the computer program @risk with the following distributions of the input variables.

*Fraction of accidents involving a single vehicle (**Y**):*
-Uniform distribution
-Maximum value – 0,6
-Minimum value – 0,3

The maximum and minimum values have been chosen from the calculation matrix in /Räddningsverket, 1996/. The maximum value represents a value for a motorway with a speed limit of 110 km/h, this value has been chosen to represent the vehicles exceeding the speed limit. The minimum value represents vehicles travelling at a speed of 70 km/h, which might be the speed for some trucks.

*Fraction of Hazardous Goods accidents resulting in spills (**C**):*
-Normal distribution
-Mean value – 0,22
-Standard deviation – 0,1

This variable increases with increased speed limit, this is based on the reasoning that vehicles travelling at a greater speed will have more kinetic energy and will therefore more likely cause greater damage to the vehicle. The chosen standard deviation will consider vehicles travelling at slightly lower/higher speeds.

*Amount of vehicles per 24 hours (**A**):*
-Uniform distribution
-Maximum value – 50000
-Minimum value - 30000

The value of 44300 vehicles per 24 hours is a prediction of how many vehicles will use the tunnel. To incorporate the uncertainties in this prediction an interval has been chosen.

*Fraction Hazardous Goods transport (**X**)*
-Normal distribution
-Mean value – 0,0024
-Standard deviation – 0,001

This value is based on statistical information from 1995, to account for the uncertainties a standard deviation of 0.001 has been chosen.

*Accident quote (**B**)*
-Uniform distribution
-Maximum value – $6,0 \cdot 10^{-7}$
Minimum value - $2,6 \cdot 10^{-7}$

This value is taken from the calculation matrix in /Räddningsverket, 1996/. The range of values chosen represents motorways with a speed limit of 70 km/h to 110 km/h.

The uncertainty analysis has been carried out on the expected number of hazardous goods accidents resulting in spills in the tunnel per year. The uncertainty analysis has been carried out with 10000 iterations using Monte Carlo sampling. The distribution of the result is shown in figure B1.

The result of the uncertainty analysis is a distribution of the expected number of hazardous goods accidents resulting in spills per year. The mean value will be used in the analysis. Due to the degree of uncertainty in the input variables the distribution of the output data will be fairly large as is illustrated in the figure below. This gives an indication of the level of uncertainty in the final results.

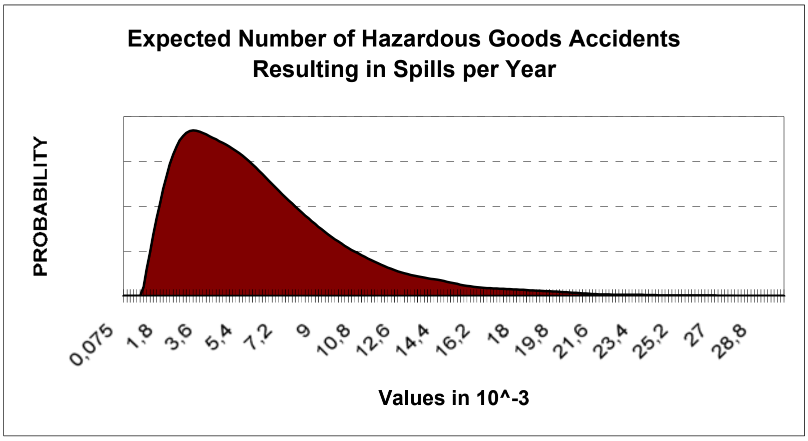


Figure B1

Mean Value	*Std. Deviation*	*5 percentile*	*95 percentile*
$5,6 \cdot 10^{-3}$	$4,1 \cdot 10^{-3}$	$6,4 \cdot 10^{-4}$	$1,4 \cdot 10^{-2}$

Finally the fraction of the different types of hazardous goods transports will be used to calculate the initial frequency for each scenario.

Type of Hazardous Goods Transport	*% of total amount of hazardous goods transports*
Gasoline	68
Propane	15
TNT	1

Table B2- /Ernst Basler, 2001/

Thus the initial frequency that will be used has been calculated as follows:

$$\frac{5{,}6 * 10^{-3}}{44300 * 365 * 0{,}0024} = 1{,}4 * 10^{-7} \text{ per year.}$$

Where 44300 is the amount of vehicles per 24 hours and 0,0024 is the fraction of the total amount of vehicles that are hazardous goods transports.
This calculated value corresponds relatively well with values that have been calculated in /Hubert, 1993/, where similar values range from $4.4 - 16 \cdot 10^{-7}$.

Appendix C- Frequency of Car and HGV accidents

The frequency for a car and HGV accident has been calculated using a very pragmatic method. This method has been used since it is impossible to accurately estimate this value without actually doing a statistical survey of the specific tunnel. Therefore values in PIARC 1999 have been used. A value of 10 cases of fire per year in a passenger car has been used and a slightly lower value of 7 has been used for HGVs. These values have been chosen by the author and can obviously be questioned. It is however believed that these values are relatively conservative. This is based on the information provided about the ELB tunnel in Germany, which is about three times longer and has almost 2.5 times the amount of vehicle flow. For this tunnel the number of cases of fire for passenger cars was 13 and for HGVs it was 9.

Assuming that 85 % of the vehicles are passenger cars the following frequencies have been calculated:

Passenger cars:

$$\frac{10}{44300 * 365 * 0{,}85} = 7{,}2 * 10^{-7} \text{ per year}$$

HGV:

$$\frac{7}{44300 * 365 * 0{,}15} = 2{,}9 * 10^{-6} \text{ per year}$$

Appendix D – Event Trees

Event trees have been constructed for accidents involving HGV, gasoline transport and a propane (LPG) transport. There is always a problem associated with a high level of uncertainty when assigning different frequencies to the branches in the event tree. The frequencies that have been used in the following event trees have been chosen after undertaking a literature study on similar events. Due to the fact that many of the frequencies used are very site specific it has been difficult to find references to the frequencies used. The event trees are however a very good tool to get an overview of the likelihood for the different scenarios, and even though there could potential be large variations in the frequencies the main hazards will still be illustrated.

HGV

For the HGV scenario, consideration has only been taken to the effect of a functioning smoke ventilation system. In order to determine the probability for ventilation failure a detailed analysis can be performed, where one considers the probability for a functioning detection system and various component failures. This is however outside of the scope of this report and a rough assumption has been made. The reliability of the smoke ventilation system depends on many factors but can generally be said to be fairly high given normal maintenance. Since the smoke ventilation system is based on the normal ventilation system that is constantly activated the reliability is expected to increase. The system can also be activated manually in the control room if the automatic detection system fails. Therefore a value of 0.9 for the reliability of the ventilation system has been used.

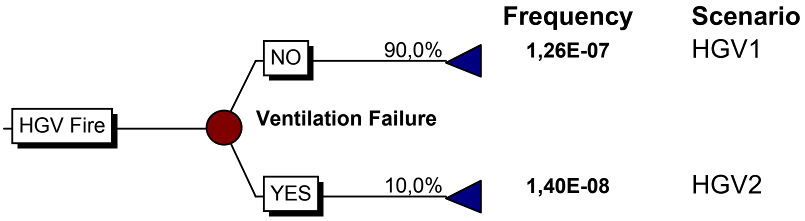


Figure D1- Event tree for HGV scenario

Gasoline Transport

In this scenario a similar event tree to that used in the Södra Länken /Rasmussen, 1994/ project in Stockholm, Sweden has been used. The approach that has been used is that the accident will result in different size pool fires. The conditions are very similar in the tunnel that is being analysed to the tunnel in the Södra Länken project therefore the same frequencies have been used.

When calculating the effect that will result from various sizes of gasoline pool fires it has been assumed that the pool size remains constant and that the fires develop according to a αt^2 fire. It will be assumed that the Q_{max} values will be reached after 45 seconds for all pool sizes and that after this point the HRR will be constant for 2 hours. In the case of an accident it is possible that very large pools will initially form but after a short period of time these fires will be limited to the pool size where the depth of the pool is sufficient to support a certain size fire. Since this analysis will consider the effect of a fire that is relatively long lasting, it will be assumed that there is a constant flow of gasoline into the pool so that the pool size (fire size) remains constant for the different scenarios. The constant size for the different pools has been assumed to be 10 m^2 for a small, 30 m^2 for a medium, and 100 m^2 for a large pool fire. A scenario where tank collapse occurs will also be considered, for this scenario a fire area of 180 m^2 will be assumed. Using these predetermined pool sizes the heat release rates (Q) have been determined using the following formula /Karlsson, 1999/.

$$Q = A * m'' * \chi * \Delta H_c$$ **equation D1**

where

A = Horizontal burning area of the fuel (m^2).
m'' = Burning rate per unit area- 0.055 kg/(m^2s) for large pools ($\geq 5m^2$).
χ = Combustion efficiency - ≈ 70 % for gasoline.
ΔH_c= Heat of combustion – 43.7 MJ/kg for gasoline.

Pool Size	*Area (m^2)*	*Q (MW)*
Small	10	17
Medium	30	50
Large	100	170
Tank Collapse	180	300

Table D1- Pool fire descriptions

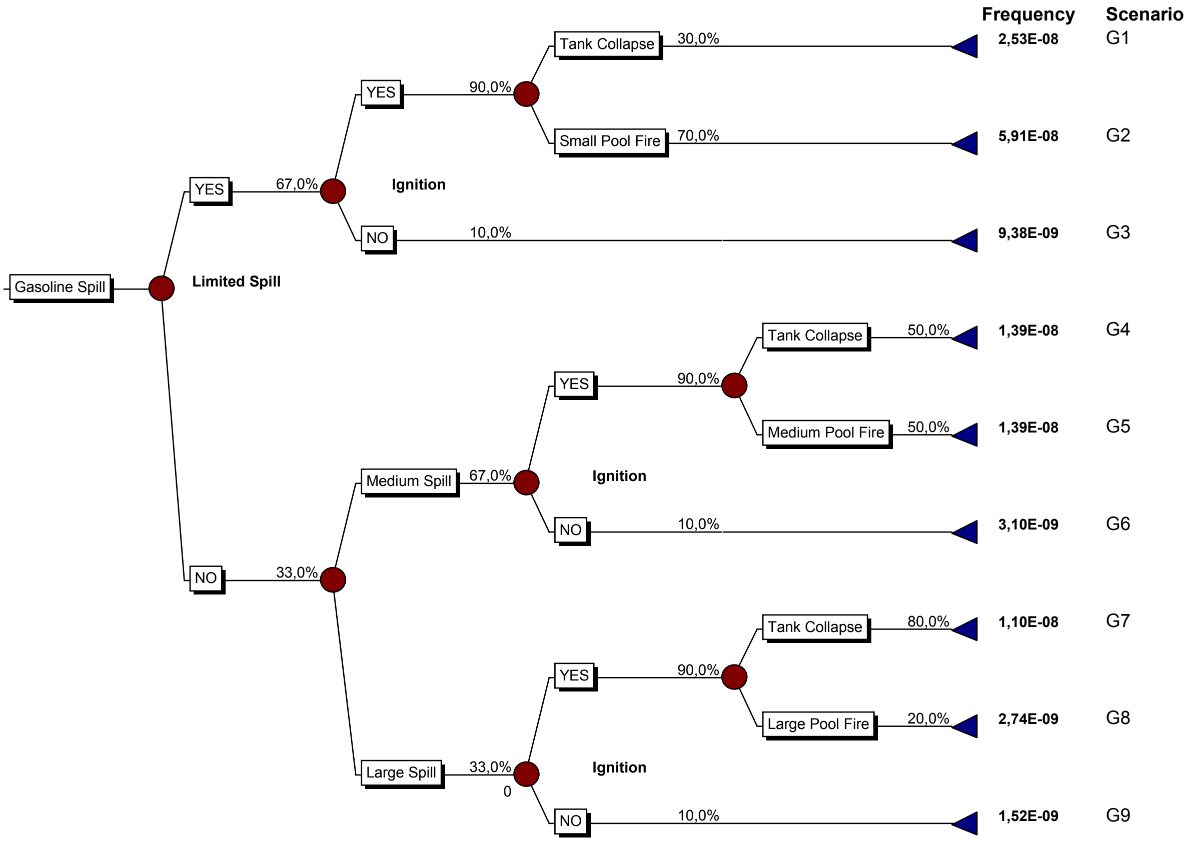


Figure D2- Event tree for gasoline scenario

Propane Transport

A transport of propane represents a transport of a flammable liquefied gas (pressure condensed). Due to the lack of statistical information regarding the different events many assumptions have been made when assigning frequencies. The frequencies used to represent a scenario have been qualitatively discussed and thereafter a frequency that to the author seems reasonable has been assigned.

A spontaneous release is the equivalent of a tank rupture leading to the whole content of the transportation being released at once. The probability of this occurring is very low since the majority of accidents resulting in a spill with this type of transport usually occur due to minor punctures of the tank or broken valves/flanges.

Equivalent ignition probabilities have been used for all scenarios.

In the case when ignition occurs of a continuous release there will initially be a flash fire (see Appendix G for a short description of the phenomena BLEVE, VCE, and Flash fire). The size of the flash fire will depend on when ignition occurs. As soon as the concentration of gas is no longer in the flammability region (2.1 – 9.5 volume % for propane) and there is a continuous release of gas a jet fire is most likely to form. If however the tank absorbs enough energy and the temperature of the liquefied gas is raised to the liquids boiling temperature at atmospheric conditions a BLEVE could potentially occur. The frequencies used for flash fire followed by BLEVE and flash fire followed by jet fire, have been taken from a scenario where the hole in the tank has been assumed to have a diameter of 0.02 m, causing a continuous release /Alp E., 1993/. For a spontaneous release a large gas cloud will form, if ignited, some form of flash fire will occur the most severe being a vapor cloud explosion. According to data collected by Wiekema /Zalosh, 1988/ 37 out of 68 reported incidents where ignition of a gas cloud in a semi-confined environment have resulted in explosions, this data has been the basis for the frequency used.

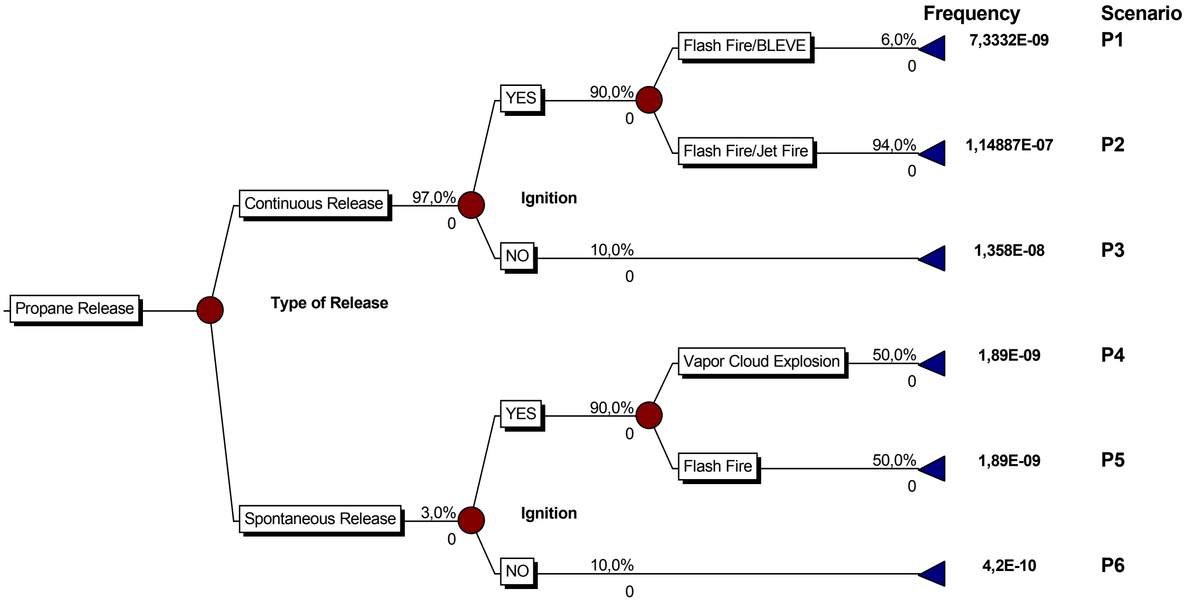


Figure D3- Event tree for propane scenario

APPENDIX E – Calculation of the Amount of People in the Tunnel

In order to calculate the amount of people that will need to evacuate the tunnel, an accident scenario has to be assumed. In all the scenarios that are analysed it will be assumed that the accident occurs in the middle of the tunnel (500m after entering the tunnel). Thus initially four different queues will form in the tunnel.

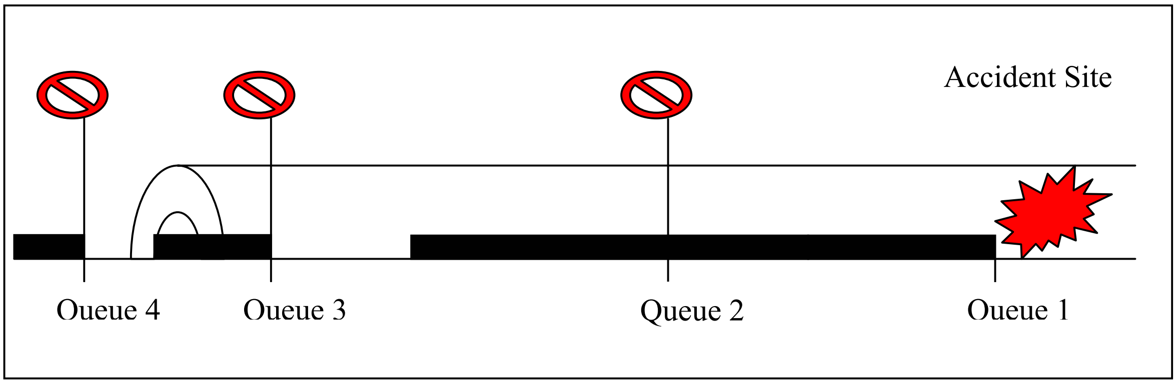
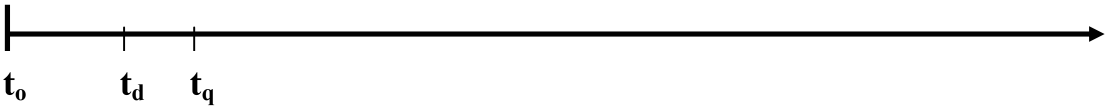


Figure E1- Initial queues formed in the queue model

The following vehicles will be considered:

Vehicle	*Length (m)*	*Percentage of the total amount of vehicles*
Cars	3,5	80
Minivans	4,5	5
HGVs	20	10
Buses	20	5

Daily 44,300 vehicles travel through the tunnel. Thus 30 cars enter the tunnel every minute, and a new vehicle enters the tunnel every other second. Thus for every minute that passes after the occurrence of an accident an additional 30 cars will join one of the queues. The average distance between the vehicles in the tunnel will thus be approximately 45 meters. The sequence of events is illustrated on the time line below.



t_0 - Time of accident, start of fire, queue 1 starts.
t_d – Detection time, time when traffic signs are activated- **2 minutes**

t_q – Queuing starts at every traffic sign – **3 minutes**

After three minutes 90 vehicles will have entered the tunnel and will be queuing directly after the accident. These 90 vehicles will form a queue approximately 270 meters long. Since the distance between queue 1 and queue 2 is 190 meters, there will not be a gap between these two queues. Therefore the only cars that will join this queue after three minutes will be the cars that are in the tunnel between queue 3 and queue 2. This is a distance of 220 meters, thus there will be an additional five cars joining the queue in the direct vicinity of the accident. This queue will then have a total of 95 vehicles. The queue will be comprised of the following

Vehicle	*People*
76 Cars á 3 people	228
5 Minivans á 5 people	25
9 HGVs á 1 person	9
5 Buses á 20 people	100

Σ 362 people

There will therefore be a total of 362 people that have to evacuate the tunnel.

Assumptions in the Queue Model

- All vehicles travel at the speed limit of 80 km/h
- The distances between the vehicles in the queues are negligible
- It will take the passengers of the vehicles 1 minute to notice the traffic signs and stop.
- People in the vehicles in queue 3 and 4 will exit into a safe area or exit safely through the opening of the tunnel.
- People will be uniformly distributed in the three zones as previously defined, ie 120 people in each zone.
- Three minutes have been added to the reaction time due to the time delay when the vehicle queue is forming.

Appendix F – Calculating the Amount of Casualties using the Fractional Effective Dose Method

The calculations using equations in section 5 have been carried out using Matlab 5.3.

The calculations have been carried out on people with an initial position of 10 meters from the fire. If the conditions were not hazardous for these people no further calculations were carried out, and the conclusion that there was no problems evacuating was draw. If however these people could not complete evacuation an analysis was carried out on people with a starting position 20 meters from the fire. Thereafter calculations were carried out in 10-meter intervals until the people in a certain position could complete evacuation. The resulting walking distances for the different scenarios are illustrated in the figures below, these walking distances represents the distance a person can reach before incapacitation. Since no consideration has been taken to fire brigade intervention it will be assumed that when incapacitation occurs people will not be able to complete evacuation. FED values as well as FLD values are also shown for several scenarios.

It has been assumed that people are evenly distributed in the tunnel and that people that are closer to the fire than the distance that has been considered will die as a result of the given fire.

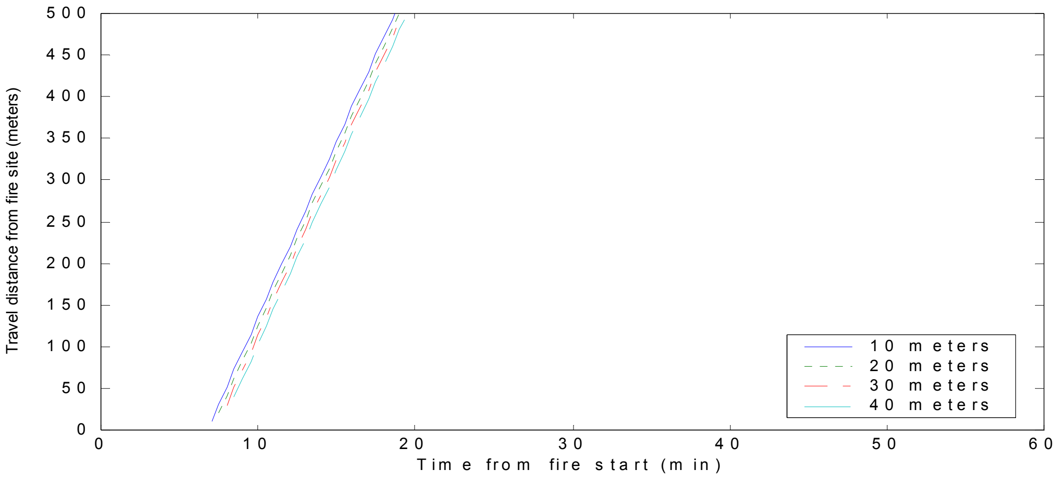


Figure F1. The theoretical walking distance during a "car fire", "HGV1", "HGV2" and small pool fire.

Figure F1 shows that for the car fire scenario people will have no difficulties completing the evacuation process. That is the critical Fractional Incapacitation Dose or Fractional Lethal Dose will not be reached. Thus for this scenario there will be no casualties.

Figure F1 also shows the walking distance for the people escaping during the HGV1 fire scenario, as figure F2 shows incapacitation will not occur before the people have completed evacuation. Therefore there will be no casualties in this scenario.

Figure F1 also shows the walking distance for the HGV2 fire scenario, and also in this case the people in the tunnel will be able to complete evacuation before either the FED or FLD reaches unity. It is however of interest to see that critical values are reached after approximately 40 minutes for people initiating the evacuation process close to the fire; this would mean fatal outcomes within 40 minutes (see fig F3) for people that are trapped in their cars. However using the methodology that has been described there will be no casualties in this scenario.

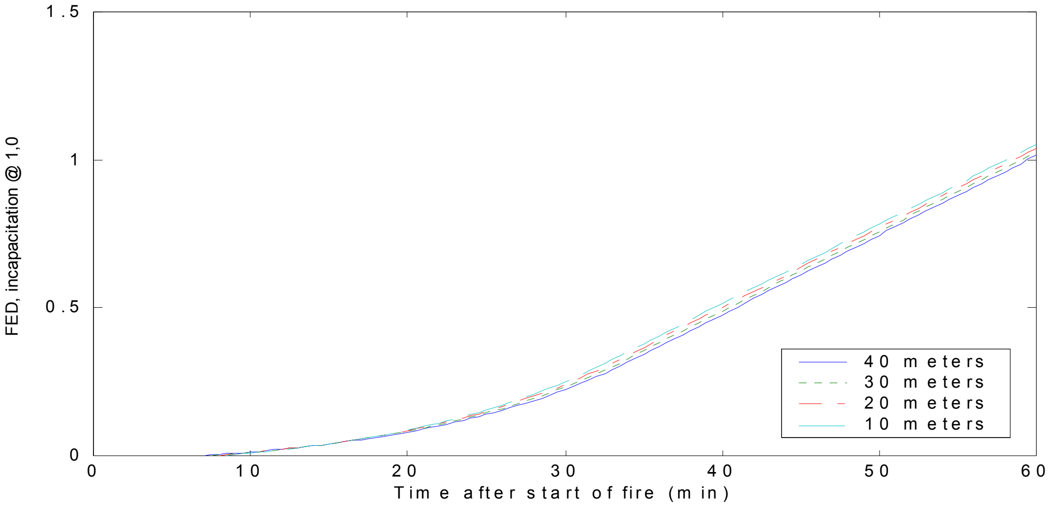


Fig F2- FED for the HGV1 fire.

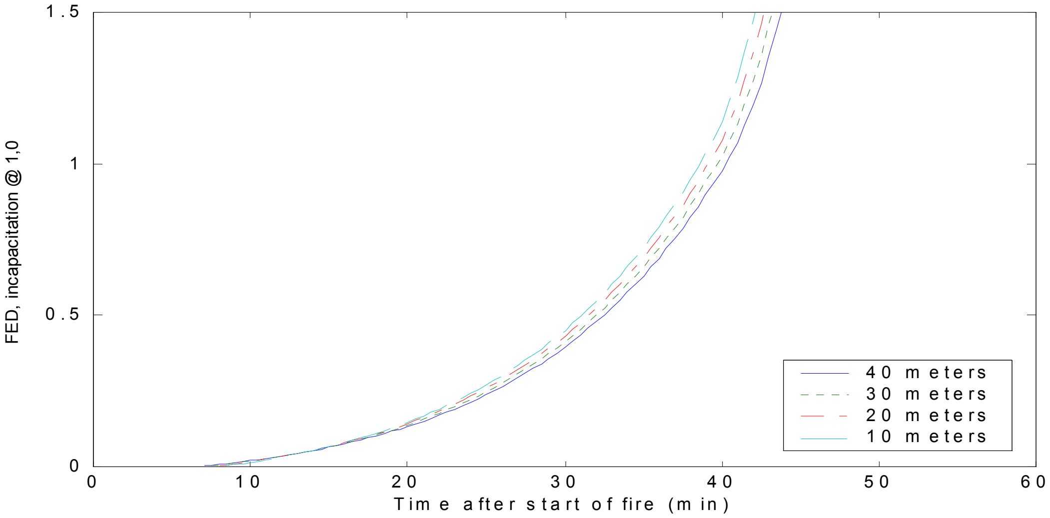


Fig F3- FED for HGV2.

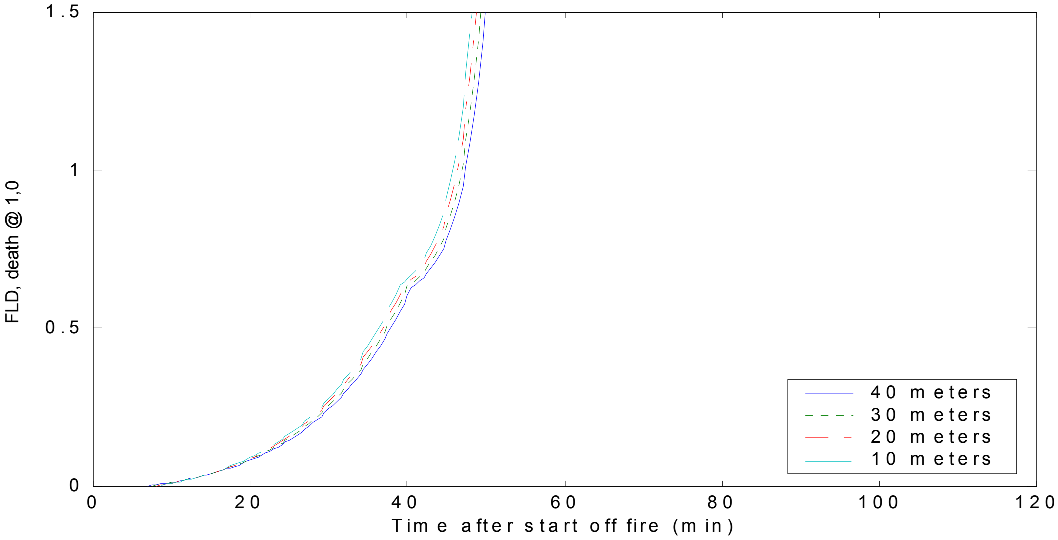


Fig F4- FLD for HGV2.

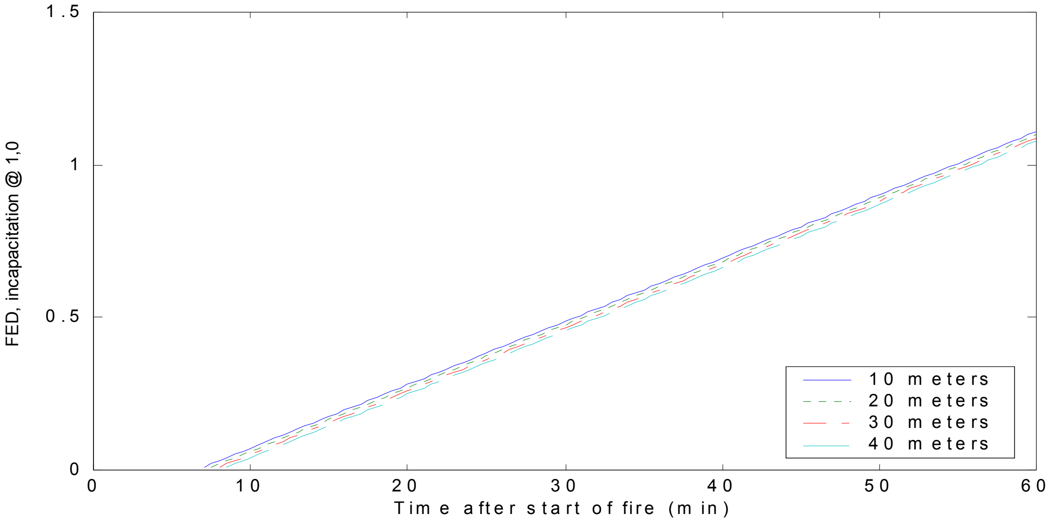


Fig F5- FED for "small" pool fire.

Figure 1 is also the walking distance for the small pool fire scenario. Figure 5 shows that critical values are reached after approximately 55 minutes for people initiating the evacuation process close to the fire. Therefore the model will predict that there will be no casualties for this scenario. By studying the radiation levels from the pool fire it was calculated that critical radiation levels were reached at a distance of approximately 11 meters from the fire (see section 5.4).

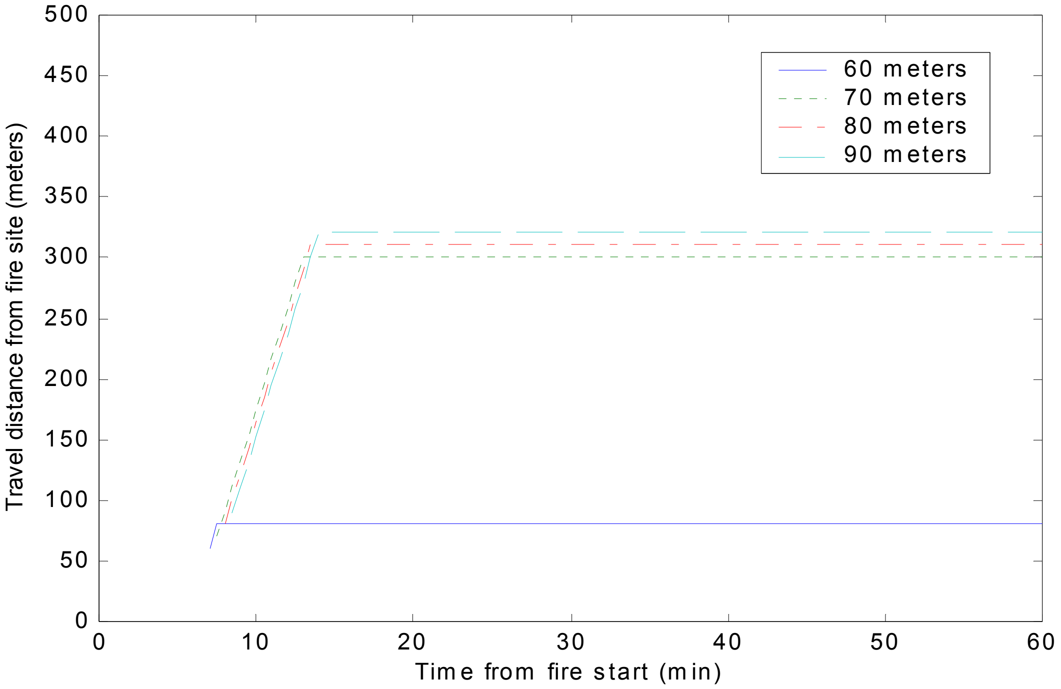


Fig F6- Walking distance for "medium" fire at various distances from fire.

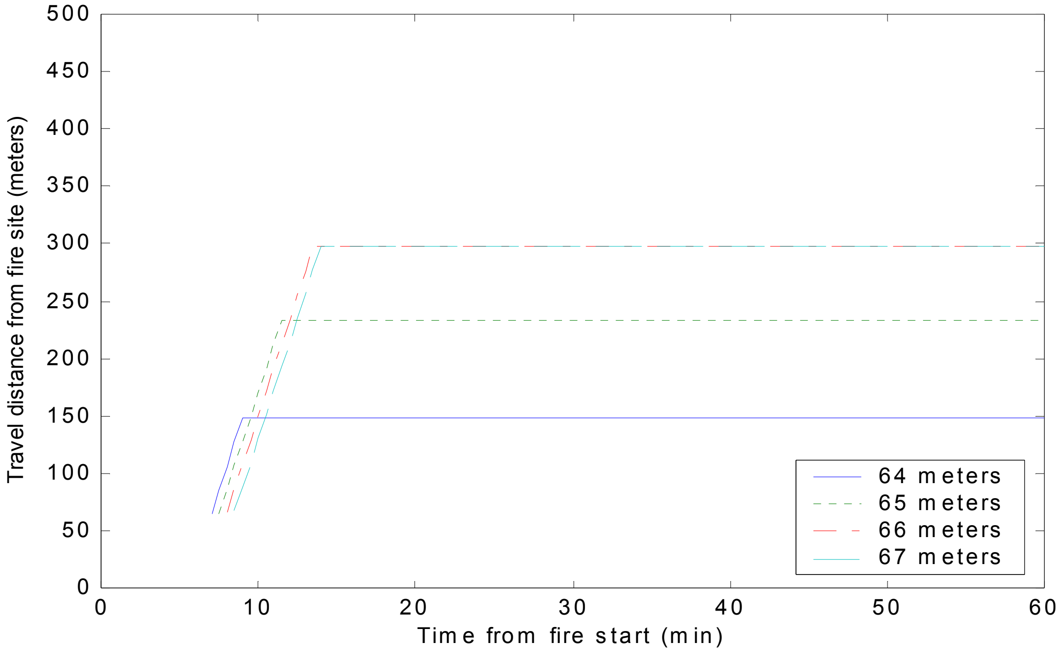


Fig F7- Walking distance for "medium" fire at various distances from fire.

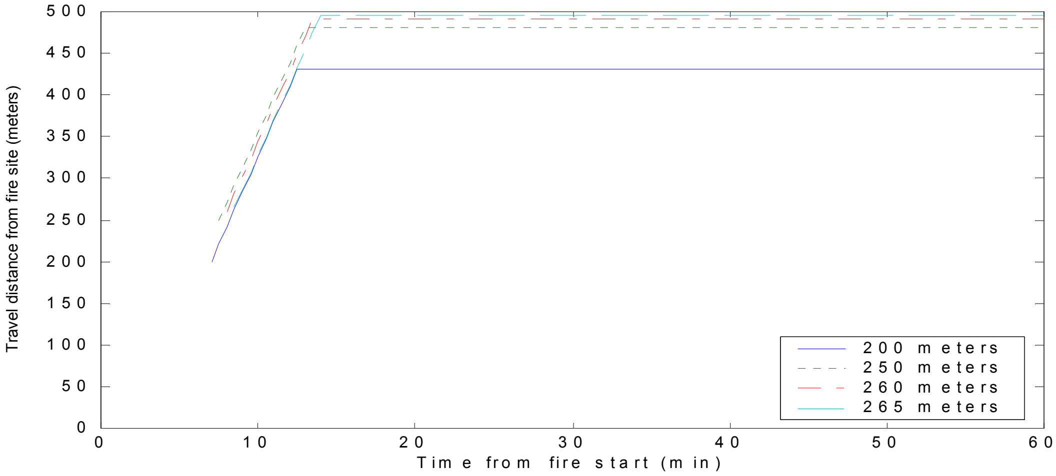


Fig F8- Walking distance for "medium" fire from various distances from fire.

Figures F6-F8 shows the walking distances for people initiating from various distances from the fire during the medium pool fire scenario. This scenario will start creating casualties. As figure F6 shows, people starting the evacuation process at a distance of 60 meters from the fire will only reach a distance of 82 meters before incapacitation, they will thus not make it to the cross passage exit. The cross passage exit is located at a distance of 167 meters from the fire (see figure 6.2.2.1). Figure F7 shows people that are closer to the fire than 65 meters will not reach the cross passage exit. As a result, the people that are closer than65 meters to the fire will die. As zone 1 contains a total of 121 people, and as stated above it will be assumed that the people will be evenly distributed in the different zones on both walk ways (for zone 1 a total of 300 meters) there will be an average of (121/300) 0.4 people per meter of tunnel. Thus in the first 65 meters there will be a total of 51.2 casualties. Figure F8 shows that the critical distance for the people evacuating through the tunnel entrance is approximately 265 meters from the fire. Thus everyone that is evacuating through the tunnel entrance and are closer than 265 meters to the fire will die. This results in 10% of the people from the remainder of zone 1 (170*0.4*0.1=6.8 people), 50 % from zone 2 (60 people) and 80 % of the people in the initial 15 meters of zone 3 (121/500=0.24 people per meter, 0.24*30*0.8=5.8 people in zone three). This results in a total of 124 casualties for a medium size pool fire.

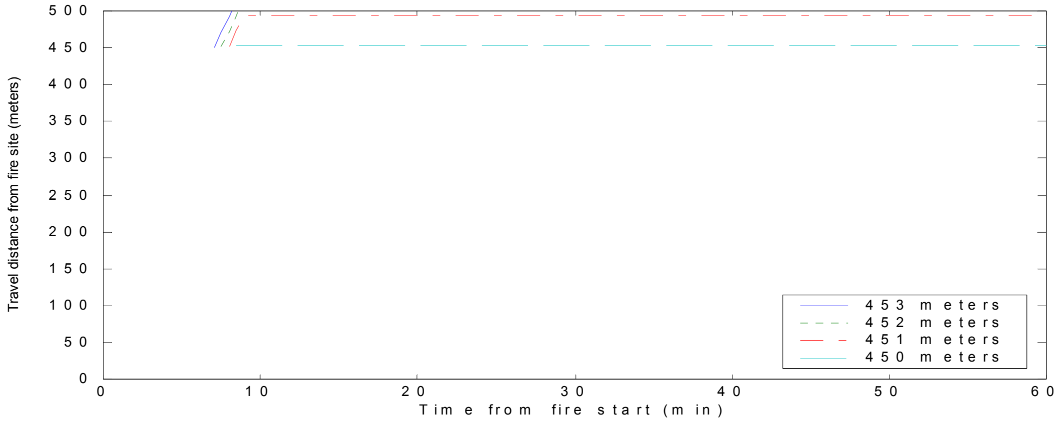


Fig F9- Walking distance for a "large" fire.

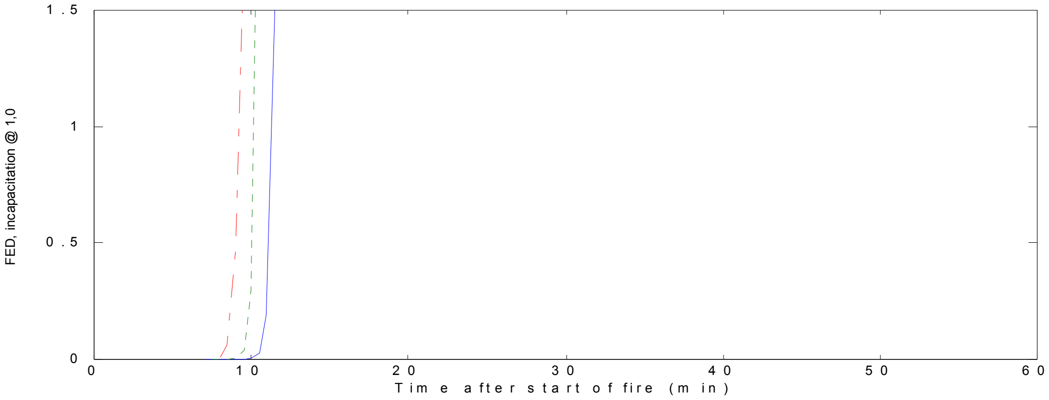


Fig F10- FED values for "large" fire for distances as in Fig F12.

Figure F9 shows the walking distance for people during the large pool fire scenario. As the figure shows only people that are initially at a distance of 452 meters from the fire will be able to complete evacuation. Therefore the amount of casualties will be as follows:

Zone1- 121 people
Zone 2- 121 people
Zone 3- 0.24 people per meter* 404 meters=97 people.

Thus a total of 339 casualties would be expected for the large pool fire scenario.

For the tank collapse scenario it will assumed that all the people that are present in the tunnel will die, the calculations show that people starting the evacuation process at distances very close to the tunnel entrance will also receive a critical dose of intoxicants. These results should however be interpreted carefully due to the amount of assumptions and uncertainties in the model.

Appendix G- Short Explanation of the Physical Phenomena BLEVE, Vapor Cloud Explosion (VCE) and Flash Fire.

A Vapor Cloud Explosion (VCE) is a physical phenomenon that may occur after the release of a flammable dangerous good such as propane. In order for a VCE to occur several conditions have to be fulfilled. These can be summarised in the following five points /Berg, 1997/.

1. The material that has been released must be flammable and at a suitable pressure and temperature.
2. The Cloud must be formed prior to ignition; once the cloud is formed the most probable ignition time delay will be between 1- 5 minutes.
3. Part of the cloud formed must be in the flammable region for the specific substance. The cloud generally consists of three zones; one rich zone where the concentrations are above the upper flammability level, this is usually near the source, one lean zone where the concentrations are below the lower flammability level. In between these zones is the flammability region.
4. Presence of turbulence, if there is no turbulence the combustion will be laminar. For laminar combustion the flame speeds are not significantly high to cause any damage in the sense of a sudden increase in pressure, when this occurs the result is a *Flash Fire*.
5. Either a deflagration or detonation has to take place. The blast effect of a VCE is determined by the speed of the flame propagation. The faster the flame propagates the higher the resulting overpressure will be. In most cases deflagration will occur, a detonation generally requires approximately a factor 10^{10} more ignition energy than a detonation.

BLEVE is a Boiling Liquid Expanding Vapor Explosion resulting from the failure of a vessel containing liquid at a temperature above its boiling point at normal atmospheric conditions. When a BLEVE occurs the vessel usually contains a combination of liquid and vapor. Before a BLEVE occurs the liquid is more or less in equilibrium with the vapor, however at the point of the vessel rupture vapor is vented and the pressure in the liquid drops significantly. At this point the liquid flashes causing a large fraction of the liquid to vaporise within milliseconds. This causes a great release of energy, which creates a high blast pressure and generates vessel fragments with high initial velocities /Doormaal, 1997/.