The Value of Safety

Evaluation on the cost effectiveness of safety measures in road tunnels in the Netherlands

June 2003
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Preface

This report is the final thesis of the masters degree of the faculty of Civil Engineering at the TU Delft. It summarises the results of the research I did at the Centre for Tunnel Safety at the Ministry of Transport, Public Works and Water Management in Utrecht.

I would like to thank the following people. First of all I would like to thank Michel Oude Essink who allowed me to do my research at the Centre for Tunnel Safety. At the Centre for Tunnel safety I would like to thank Jelle Hoeksm for sharing his knowledge and a lot of experience on tunnel safety with me, Ben Rigter and Hans Huiben for their knowledge on sprinkler installations and Bas Jonkman for the interesting discussion about safety in tunnels. I want to thank Reny Juta for the splendid coffee she offered me, Marco Smulders for supplying me with some good music during my research and Nina Breikers and Sylvia Gerritsen van der Hoop for the nice times we had during lunch.

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At the TU Delft I want to thank my graduation committee; Mr. J.K. Vrijling, Mr. P.H.A.J.M. Van Gelder and Mr. G. Arends. Finally I want to thank Wietske Rodenhuis for her moral support and critical notes on my research.

Bunno Arends,
Utrecht, June 2003
Summary

Safety in tunnels has been an issue ever since the construction of the first tunnel in the Netherlands (Maastunnel, 1942). For a few decades the majority of tunnels that were constructed were immersed. While their designs showed much resemblance, their safety concept was much alike. During the ‘90’s this standard concept changed due to the introduction of bored tunnels and land tunnels. Besides, the length of tunnels gradually increased and the debate on transport of dangerous goods resulted in less restrictions on the national highway for this type of transport. Finally, multiple use of space is becoming more and more popular. This means that tunnels become a part of a multi-level system, which has a large impact on the safety concept. Therefore the safety concept had to be evaluated. The two major fires in tunnels in the Swiss Alps (Mont Blanc 1999 and St. Gotthardtunnel 2001) fuelled the public aversion of tunnel accidents and brought safety in tunnels even higher on the political agenda. This gave rise to the question whether our safety budget is spent in such a way that the highest possible safety level in our tunnels is reached.

Hence the aim of this research was to investigate the cost effectiveness of safety measures in road tunnels in the Netherlands, comparing the investment costs related to safety measures on one hand and their effect on the risk on the other. For this purpose three different tunnel types were investigated: a bored, a land and an immersed tunnel. An effort was made to find an economic optimal safety level for these three tunnels.

An inventory of the causes of accidents in tunnels showed that are three types of accidents: normal accidents (that also occur on the rest of the highway), jammed accidents (where people get stuck in the vehicle as a result of the accident and have to be freed by the fire department, which is a little more difficult in a tunnel environment) and calamities (accidents with a very low probability, but with a large consequence, e.g. an exploding tanker). The normal accidents account for more than 90% of the expected fatalities, the jammed accidents for about 9% and the calamities for less than 1%.

In the Netherlands the number of accidents per million kilometres travelled per vehicle appears to be slightly higher in tunnels than on the open road. Nevertheless, while the Dutch highway system has a relatively low accident frequency, Dutch tunnels are considered to be among the safest in Europe.

The evaluation of the risks in tunnels was done using the probabilistic method. In this method, an inventory is made of all possible consequences of accidents in tunnels. All these scenarios are then assigned probabilities. For this investigation, the consequences of accidents were expressed in fatalities, injuries and material damage. In order to come to an economic evaluation of safety, a monetary value was assigned to all casualties. The risk of tunnel accidents can then be calculated by the sum of the damage costs of every scenario times its probability.

Of the safety measures applicable to tunnels, a division was made into structural measures (related to the tunnel configuration, like emergency exits), installations (e.g. ventilation and detection systems) and regulatory measures (e.g. speed reductions and separating the transport of dangerous goods). Of the possible safety measures, the costs for implementation, maintenance and renovation were investigated, as well as their effect on the level of safety of the tunnel.

This investigation showed that it is not possible to find an economic optimum safety level for tunnels using the same approach as is used in economic analysis.
on flood defence systems. The main reason is that the basic approach of the
cost optimisation of the flood defence system depends on just one safety
measure that can be applied at various levels (height of the dyke), while there
are numerous ways to improve safety in tunnels. An economic optimum safety
level for tunnels therefore can only be found by comparing all sorts of
combinations of safety measures.

While both the investment and the risk could be expressed solely in money, the
cost efficiency of safety measures could be made visible. The costs of safety
measures were therefore plotted in relation to the risk for the tunnel as built
(taken as a reference), and for all safety measures under consideration.

It is concluded from this probabilistic investigation of safety measures, that
increasing the number of emergency exits, construction of a shoulder and
installing a sprinkler system are all not cost effective. Concerning the removal
of safety equipment, removing the fire equipment turned out to be cost
effective. This indicates that the safety levels of the tunnels as they are
designed at the moment depend not only the probabilistic approach on safety.
Finally it is concluded that in relation to the tunnels as they are built, safety
measures like a fire resistant lining are very cost efficient. The most cost
efficient safety measures in tunnels are the regulatory measures like the
introduction of a minimum distance between vehicles and enforcing speed
reductions. Besides the influence of human behaviour in case of a tunnel
accident is very important. Therefore it is recommended to do more research
on the human behaviour.

For the cost effectiveness of safety measures in relation to the three different
types investigated, it can be concluded that the differences in costs for safety
measures for a Land and Immersed tunnel are very little. The choice between
safety measures therefore mainly depends on the length of the tunnel, the daily
traffic volume and the number of trucks transporting dangerous goods. Besides
the main differences in costs for safety measures for the three tunnel types, are
the costs related to structural safety measures. For a Bored tunnel the costs
related to structural safety measures are high compared to the other two. This
means that in a cost optimisation of safety measures for a Bored tunnels, the
focus should definitely be on traffic management solutions.
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<th>Full expression</th>
<th>Explanation</th>
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<tr>
<td>Accident frequency</td>
<td>Statistical distance a vehicle travels between two accidents, so the number of accidents divided by the number of vehicles times the length of a tunnel</td>
<td></td>
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<tr>
<td>BLEVE</td>
<td>Boiling Liquid Expanding Vapour Explosion</td>
<td>Delayed explosion of a tanker loaded with flammable cargo</td>
</tr>
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<td>BOMVIT</td>
<td>&quot;Beslissings Model voor Vluchtstroken In Tunnels&quot;</td>
<td>Probabilistic model developed at the Ministry of Transport, division road design in Apeldoorn. It evaluates the relation between the investment costs of constructing a shoulder with the decrease in risk of tunnel accidents.</td>
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<tr>
<td>Category (of dangerous goods)</td>
<td>Classification of the tunnel according to the transport of dangerous goods that is permitted</td>
<td></td>
</tr>
<tr>
<td>Category 0</td>
<td>No restrictions</td>
<td></td>
</tr>
<tr>
<td>Category I</td>
<td>Exclusion of toxic goods and explosives, no restriction on LPG and tankers</td>
<td></td>
</tr>
<tr>
<td>Category II</td>
<td>Exclusion of LPG and tankers, no restriction on diesel trucks</td>
<td></td>
</tr>
<tr>
<td>CV</td>
<td>Characteristic Value</td>
<td>A value that takes into consideration the social aversion of the public towards calamities, usually calculated as the EV plus three times the standard deviation</td>
</tr>
<tr>
<td>damage costs est.</td>
<td>estimated damage of a scenario</td>
<td></td>
</tr>
<tr>
<td>EV</td>
<td>Expected Value</td>
<td>Sum of probabilities times the consequence for all scenarios</td>
</tr>
<tr>
<td>EVcosts (€)</td>
<td>Expected Value of material damage costs in Euros</td>
<td>Sum of probabilities times the expected material damage costs per scenario</td>
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<td>EVjammed (N)</td>
<td>Expected Value of fatalities for jammed people</td>
<td>Sum of probabilities times the expected number of fatalities as a result of &quot;jammed&quot; people</td>
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<tr>
<td>EVnormal (N)</td>
<td>Expected Value of fatalities for normal accidents</td>
<td>Sum of probabilities times the expected number of fatalities as a result of &quot;normal&quot; accidents</td>
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<td>EVsplc (N)</td>
<td>Expected Value for splc accident</td>
<td>Sum of probabilities times the expected number of fatalities for all &quot;splc&quot; scenarios</td>
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<td>Fn-Curve</td>
<td>Graphic representation of the estimation of the frequency (F) versus the number of fatalities (N), both on a logarithmic scale</td>
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<td>GF</td>
<td>Gas Flammable</td>
<td>Number of trucks transporting Flammable Gas</td>
</tr>
<tr>
<td>GT</td>
<td>Gas Toxic</td>
<td>Number of trucks transporting Toxic Gas</td>
</tr>
<tr>
<td>HCA</td>
<td>Human Capital Approach</td>
<td>Method to validate the loss of a statistical life, see paragraph 4.3.1</td>
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<tr>
<td>jammed</td>
<td>People stuck in a vehicle due to an accident</td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>Liquid Flammable</td>
<td>Number of trucks transporting Liquid Flammable goods</td>
</tr>
<tr>
<td>LT</td>
<td>Liquid Toxic</td>
<td>Number of trucks transporting Liquid Toxic goods</td>
</tr>
<tr>
<td>normal</td>
<td>&quot;normal&quot; accident</td>
<td>&quot;normal&quot; accidents are comparable to accidents on the open road, e.g. head-on collisions</td>
</tr>
<tr>
<td>PV</td>
<td>Present Value</td>
<td>Value that shows costs over a certain period as given in the prices of the base year, including the depreciating of money (discount rate)</td>
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<tr>
<td>pdf</td>
<td>probability density function</td>
<td></td>
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<tr>
<td>risk</td>
<td>The sum of the probability times the damage costs of all scenarios</td>
<td></td>
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<tr>
<td><strong>SDS</strong></td>
<td><strong>Speed Detection System</strong></td>
<td>Electric loop in the asphalt that measures the speed of all vehicles, and gives an alarm when the speed of a vehicle crosses a fixed minimum level.</td>
</tr>
<tr>
<td><strong>splc</strong></td>
<td><strong>Small Probability Large Consequence</strong></td>
<td>Accidents with a very low probability, but with serious consequences.</td>
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<tr>
<td><strong>Self-help</strong></td>
<td></td>
<td>Ability of people to flee an emergency situation on their own</td>
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<tr>
<td><strong>Shoulder (hard shoulder)</strong></td>
<td></td>
<td>Extra traffic lane that is used to park your vehicle in case of emergency</td>
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<td><strong>TunPrim</strong></td>
<td></td>
<td>Probabilistic model on the internal risks of road tunnels, developed at the Ministry of Transport, division of tunnel safety in Utrecht</td>
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<td><strong>UMS</strong></td>
<td><strong>“Uitsluitend Materiële Schade”: Only Material Damage</strong></td>
<td>Accidents with only material damage (no casualties)</td>
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<tr>
<td><strong>VSL</strong></td>
<td><strong>Value of a Statistical Life</strong></td>
<td>Method to validate the loss of a statistical life, see paragraph 4.3.1</td>
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<td><strong>WST</strong></td>
<td><strong>Westerscheldetunnel</strong></td>
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<tr>
<td><strong>WTP</strong></td>
<td><strong>Willingness To Pay</strong></td>
<td>method to validate the loss of a statistical life, see paragraph 4.3.1</td>
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<td>$\sigma_{\text{costs}}$ (€)</td>
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<td>Standard deviation of material risk (in €)</td>
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<td>$\sigma_{\text{jammed}}$ (N)</td>
<td></td>
<td>Standard deviation of the number of fatalities of jammed people</td>
</tr>
<tr>
<td>$\sigma_{\text{normal}}$ (N)</td>
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<td>Standard deviation of the number of fatalities as a result of normal accidents</td>
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<td>$\sigma_{\text{splc}}$ (N)</td>
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<td>Standard deviation of the number of splc fatalities</td>
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Introduction

Safety in tunnels has been an issue ever since the construction of the first tunnel in the Netherlands (Maastunnel, 1942). For a few decades the majority of tunnels that were constructed were immersed. These tunnels crossed waterways and had a relatively short distance, usually a few hundred meters. The similarity in the design of these tunnels resulted in a safety concept that was much alike. During the ‘90’s this standard concept changed for various reasons. First of all the introduction of bored tunnels and land tunnels changed the configuration of tunnels. Besides, the length of tunnels gradually increased. The debate on transport of dangerous goods resulted in less restrictions for this type of transport. Finally, multiple use of space is becoming more and more popular. This means that tunnels become a part of a multi-level system, which has a large impact on the safety concept. All these changes had a great impact on the standard safety approach that was used until then.

Therefore the safety concept had to be evaluated. This was the start of a new and broad discussion about safety in tunnels. Research was started to investigate whether the safety approach for immersed tunnels could also be applied to this new generation of tunnels. Other questions were how the level of safety in tunnels can be increased and the possibility to develop a standard safety concept for all types of tunnels.

The two major fires in tunnels in the Swiss Alps (Mont Blanc 1999 and St. Gotthardtunnel 2001) fuelled the public aversion of tunnel accidents and brought safety in tunnels even higher on the political agenda. As a result, more money became available to prevent such disasters. This gave rise to the question whether our safety budget is spent in such a way that the highest possible safety level in our tunnels is reached. This question is relevant, because investigations on cost effectiveness of safety measures in other fields show that this is not automatically the case. Thus it is necessary to investigate the relation between the gain in safety versus the costs involved, in other words: the cost effectiveness of safety measures.

Hence the aim of this research is to investigate the cost effectiveness of safety measures in road tunnels in the Netherlands. This economic analysis comprises the costs related to safety measures on one hand and their effect on the risk on the other. The tunnel as built is taken as a reference point. For this purpose three different tunnel types were investigated: a bored, a land and an immersed tunnel. An effort was made to find an economic optimal safety level for these three tunnels.

The first chapter investigates the risks in tunnels. Then a description of two ways to evaluate safety is presented in chapter 2. An overview of possible safety measures applicable to tunnels is given in chapter 3. The next chapter (4) focuses on the risks related to tunnel accidents. Now that both costs of safety measures and the risk are clear, an investigation is done on three tunnel cases (chapter 5). The results of these investigations are evaluated in chapter 6. Finally conclusions and recommendations following from this research are

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1 In her annual speech to the Dutch cabinet on the 17th September 2002, her majesty mentioned that “the improvement of safety in tunnels will get more attention”.

2 A study in the US [1], in May 1997 shows that the investments made in that year in the health sector, could have saved more than twice as much life years if it were invested in the most cost-effective regulations: $ 4.11 billion was spent saving 94,000 life years, the same amount would have saved 211,000 life years.
presented in chapter 7. A schematic overview of the process of the project is given in Figure 0-1.

Figure 0-1: Schematic representation of the process of the cost effectiveness analysis in this report

A lot of material that was used for this research is confidential. Because the aim of this research is to contribute to the broad discussion about safety, a fully confidential report was not favoured. Therefore the main report is written for the general public and all confidential material that was used is presented in the appendices. The appendices are therefore confidential.
1 Causes of risks in tunnels

The risks in tunnels are the product of the probability of accidents (paragraph 1.1) and their consequences (paragraph 1.2). While these two paragraphs are only qualitative descriptions of risks in tunnels, a paragraph (1.3) with statistics on tunnel risks is added, to get a quantitative idea about the risks in tunnels. Finally an overview of the causes and results of tunnel accidents is given (paragraph 1.4).

1.1 Causes of accidents

Road tunnel accidents have various causes. Most of them are implicit to the road transport system as a whole (1.1.1), others are directly related to the tunnel environment. (1.1.2).

1.1.1 General causes of accidents

A broad inventory of the causes of road accidents gives the following [2]:
- Physical causes (storm, extreme rainfall, lightening, fog)
- Technical failure (failure of the vehicle, bad maintenance, poor design)
- Human failure (sudden panic reactions, steering mistakes, inattention, becoming unwell)
- Criminal behaviour (theft of safety equipment, arson, terrorist activities)

Of these causes, the physical causes are less relevant in tunnels and criminal behaviour is hard or impossible to fight. Human and technical failure on the other hand can be influenced. Therefore the focus of this research is on technical and human failure, which can best be described on a system level. A study [3] relates accidents to the three key components of the road transport system: the road, the vehicle, the driver, and their interaction

- The road can be described as the construction itself, the installations and equipment, and the surroundings. Characteristics of the road highly influence the driving capacity. A thorough design according to the guidelines made by the Ministry of Transport can optimise road characteristics. There are special guidelines for the design of tunnels [4].
- The vehicle has properties like type, age, technical state and, in the case of trucks, the type of load (normal, flammable or hazardous).
- The driver is a key factor in traffic. Participating in traffic is a difficult task. Decisions have to be made and actions have to be taken under time pressure. The demands on a driver vary considerably. What seems to be a routine operation can change within a second to an emergency.

Accidents are usually a combination of these three elements. But also the interaction between road users is very important. For instance the chances of accidents decreases when the differences in speed and weight in the traffic flow are less. Besides, the number of vehicles is important, because there is a relation between the traffic intensity and the accident frequency.

\(^3\) Accident frequencies are expressed per million vehicle kilometres which is the statistical distance one vehicle travels between two accidents. So the total amount of accidents is the product of the
The Ministry of Transport\(^4\) can therefore influence the level of safety of a highway system by changing the properties of the:

- **road**: a thorough design of the road can decrease the accident frequency
- **vehicle**: requirements on properties of cars or the permission of dangerous goods influence the level of safety.
- **driver and traffic**: traffic management solutions can influence the performance of individual drivers and their interaction.

1.1.2 Causes of accidents in tunnels

Besides the general causes of accidents on highways, there are specific reasons for accidents in tunnels. Some are related to their different configuration, others are due to the different psychological effects on the driver. On the other hand there are also some positive aspects of tunnels that decrease the accident frequency.

**Physical causes of accidents in tunnels**

The following physical aspects of tunnels influence the accident level.

- **Alignment and visibility**: a complex configuration of a tunnel can result in an increase of tunnel accidents, due to difficulties with orientation in a tunnel. Also the walls of the tunnel can block the view of a traffic jam just around the corner.
- **Vertical alignment and speed differences**: slopes can influence the speed of the driver. The speed may increase downhill and decrease uphill, (depending on the steepness) due to a lack of visual information in the tunnel. Moreover the weight of trucks induces more speed differences as a result of the slopes. Another factor is that a long descend can cause speeding and loss of control over the vehicle or overheating of breaks.
- **The traffic volume influences the accident frequency as well.** Low traffic intensities usually result in large speed differences and thus a relatively high accident frequency. A congested tunnel in general has a low accident frequency, because the traffic flow is uniform and slow.

**Psychological effects of a tunnel on the driver of a car**

Participating in traffic is a constant process of gaining and handling information about the surroundings. This is normally an automatic process. The level of performance of handling this information depends on the capacity of the driver. When driving is perceived easy, the driver does not use his total capacity and is able to relax. However when the task becomes more complicated, the pressure on the driver increases. A normal reaction of the driver is to try and normalize the pressure, which can be done by [3]:

- increasing his capacity, for example with a more active attitude and a more alert approach
- simplifying his task, usually by lowering his speed or avoiding difficult manoeuvres like overtaking.

This decision process is mainly influenced by the properties of the road, its surroundings and the other participants on the road. A tunnel has a great impact on the pressure experienced by a driver. A description of some factors

\(^4\) In cooperation with the Ministry of Housing, Spatial Planning and Environment and the Ministry of Justice
that influence the perception of pressure of a driver while driving through a tunnel is given below:

- **Distance between the driver and the walls of the tunnel:** in general the closer a person is to a wall, the more pressure he experiences.
- **Amount of light in the tunnel:** if the amount of light in the tunnel is different from the level outside, the eyes of the driver need to adapt. The bigger this difference is, the more time is needed for this adaptation. Drivers tend to reduce their speed and steer a little bit more to the middle of the road. Further into the tunnel, the speed slowly increases to the original level.
- **Length:** because long tunnels usually have a monotonous nature, it can negatively effect the concentration of the driver.

The above-mentioned factors all increase the perceived pressure of the driver. As a result he tends to make more mistakes or reduces his speed in order to balance the level of information he receives with his capacity to act. A complication hereby is that people are not alike. The way people act while entering a tunnel differs, causing an increase in the turbulence of the traffic flow. These sudden differences in speed have a negative influence on the level of safety. It is found in Norway [8] that most of the accidents in tunnels take place in the tunnel entrance or just ahead\(^5\).

### Positive effects of tunnels on road safety

Besides these negative effects, driving through a tunnel also takes away some of the general causes for accidents, because these risks do not exist in tunnels [2]:

- The tunnel is a closed system and therefore a blockage of the road by an object like a falling tree is not likely.
- Weather conditions are better in tunnels; there is no snow, rain, fog nor wind.
- The tunnel usually has a simple layout, where crossings and ramps are avoided.
- People tend to be more alert in tunnels in order to increase their driving capacity.
- Tunnels are generally well lit and often supervised.
- Traffic is often slow, reducing the opportunity for high-speed relative motion between vehicles.

### Combination of the positive and negative aspects on tunnel safety

If the negative aspects of tunnels (different physical configuration and psychological pressure on the driver) and the positive aspects are summed, it seems that both aspects are of the same magnitude. Studies in France [2], Germany [5] and the U.S.A [6] found generally lower accident frequencies in tunnels compared with the open road. However, the accident frequencies vary considerably per tunnel, so some have a higher accident frequency than the average frequency on the open road. In the Netherlands the accident frequency found for tunnels is higher than on the open road. Important for the accident frequency is the total length of the tunnel. Usually the accident frequency in the tunnel entrances is higher than on a normal road, while in the straight part the accident frequency is lower. Thus the average accident frequency per kilometre for short tunnels is generally relatively high and lower for long tunnels.

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\(^5\) In Norway it is reported that the accident ratio per million vehicle kilometres is at the entrance in the order of 0.5 to 0.8 while in the tunnel this is about 0.1 till 0.2.
1.1.3 Tunnels in the Netherlands
If we look at the Dutch situation, unfortunately we find higher accident frequencies in tunnels than on the open road. An explanation can be that the tunnels are generally short. Besides, the accident frequency on the open road is one of the lowest in Europe. Still, the number of casualties in Dutch tunnels is very low.

Other characteristics are the high traffic volumes in Dutch tunnels. A lot of attention is paid to the design of the entrances to avoid entering a “black hole” and the vertical and horizontal alignment are kept as simple as possible. Finally highway tunnels in the Netherlands are always uni-directional in order to prevent head-on collisions and for a better ventilation regime. Dutch tunnels therefore are among the safest in Europe.

1.2 Effects of accidents in tunnels
Due to its closed configuration, the consequences of an accident in a tunnel have the potential to aggravate and are usually larger than on the open road. The following aspects of a tunnel have a negative influence on the amount of casualties.

- the tunnel is an obstacle that can be hit by a car that leaves the traffic lane.
- the consequences of fires are worse compared to the open road. By-products of fires like (toxic) gasses, smoke and heat can pose a threat to human lives. While these products can only leave the tunnel at the two entrances, the area of influence of an accident is larger than out in the open. Furthermore, there is always airflow in the tunnel (sometimes due to artificial ventilation) that increases the speed of the diffusion of heat and gasses.
- the closed configuration makes it difficult to flee an emergency situation, because the traffic may be trapped and the number of emergency exits is limited.
- the tunnel makes it difficult for the fire department and medical care to reach the accident (in time). Moreover they have to enter the tunnel in the opposite direction of the people who are fleeing the emergency situation. Depending on the ventilation regime, they may also have to operate in the opposite direction as the smoke.

Besides, there are also negative aspects related to the material damage. A fire in the tunnel does not only affect the asphalt (like on the open road), but may also harm the equipment in the tunnel, the tunnel structure and in an extreme situation pose a threat to the integrity of the tunnel.

1.3 Statistics on road tunnel accidents
When examining the chances of accidents in tunnels, a first impression is gained by looking at the statistics on road safety. A study done in the European Union shows a total of 38,000 fatalities in road traffic each year, which is one every 15 minutes! When this number of fatalities is expressed in an average accident frequency of 1.5 accidents per million vehicle kilometres, whereas on the rest of the highways this number is 0.57 [56].

A survey of the department of traffic management in 1986-1987 involving 6 tunnels showed an average accident frequency of 1.5 accidents per million vehicle kilometres, whereas on the rest of the highways this number is 0.57 [56].

Up to now only one major accident occurred in the Velsertunnel in 1978 (with 5 fatalities).

Expected in this study for the year 2000
accident frequency (fatalities per billion km), it is the most dangerous way of transportation we know. Fortunately large reductions in fatalities in the European Union member states have been accomplished during the last decade (about 24%) [7].

However, the decreasing trend in fatalities over time seems to flatten out. Contrary to the decreasing trend in fatalities in road traffic in general, there are some indications that the total number of fatalities may increase. It is expected that the number of fatalities per accident will stay at the same level or drop a little bit (improvements in the crash performance of cars). The number of accidents however is expected to increase due to rising traffic densities. Added to this are other factors that increase the potential hazards of traffic tunnels: [9]

- increasing length of modern tunnels (in the Netherlands e.g. the Westerscheldetunnel)
- higher loading capacities for trucks
- increasing amount of transport of hazardous materials
- the general policy regarding the transport of hazardous goods is to reduce the number of restrictions on the national highway system, so there is a movement towards fewer restrictions on transport of dangerous goods through tunnels.

Appendix A.1 gives an overview of the reported fatalities in road tunnels in the world and in Europe. The total number of casualties in tunnels in Europe in the period between 1974 and 2001 was 104, which means an average of about 4 per year in absolute terms. This is very low in comparison to the amount of 38,000 fatalities that are experienced annually in road traffic in total in the European Union.

The following statistics give some characteristics on risks in tunnels

- A collision rarely leads to a fire; most fires are caused by the electrical installation of the car. For trucks the main reason for a fire is over heating of the breaks. [10]
- Of the fires in road tunnels, 95 % is caused by a defect of the car [3].
- Of the fires in tunnels, about 80 % to 90 % do not have consequences for people or equipment and are therefore harmless [11].
- Heavy traffic is involved in 30 % of the lethal accidents [12].
- Of the freight transported 5-10 % is hazardous. From this dangerous cargo, about 60 % is flammable (mainly fuel).
- The European Commission forecasts that between 1998 and 2010, passenger vehicle traffic will likely increase by 21 % (average of 2 % per year) and road freight traffic by 38 % (average of 2,7 % per year). This traffic growth will place additional pressure on Europe’s roadway tunnels [29].
- In 1991, the Dutch government spent about € 90 million on traffic safety. The same year the total damage was estimated to be € 3.200 million [13].

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9 Individual risk figures in fatalities per billion transport kilometres in the Netherlands show a rate of 14,1 for passengers in road transport (1994), 0,19 for train passengers and 0,4 for European civil aviation. [8]

10 Tunnels in Europe, including those in Switzerland

11 Though one must realize that the total length of all tunnels is considerably lower than the total road system in Europe.
1.4 Overview of the causes and consequences of tunnel accidents

The table below (Table 1-1) presents an overview of the causes of accidents in road tunnels, the situations in which they occur and their consequences.

<table>
<thead>
<tr>
<th>Accident situation / disturbance</th>
<th>Cause</th>
<th>Result (that can occur)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Traffic jams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Before the tunnel entrance</td>
<td>traffic intensity is (too) high</td>
<td>Chances of accidents increase</td>
</tr>
<tr>
<td>• In the tunnel</td>
<td>(too) short intervals between cars</td>
<td>Increase the influence of the consequences of an accident (people can get stuck)</td>
</tr>
<tr>
<td></td>
<td>large turbulence in the traffic flow</td>
<td>increase the risk of a head and tail collision and can obstruct the fleeing paths</td>
</tr>
<tr>
<td>2. Collisions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• uni- or bi-directional tubes</td>
<td>regular accidents (as on “normal highways”)</td>
<td>more collisions</td>
</tr>
<tr>
<td>• head-tail</td>
<td>accidents due to specific geometry of the tunnel</td>
<td>traffic jam</td>
</tr>
<tr>
<td>• one sided</td>
<td></td>
<td>loss of dangerous goods</td>
</tr>
<tr>
<td>• side</td>
<td></td>
<td>fire</td>
</tr>
<tr>
<td>• frontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Local blockage of lane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• vehicle on the traffic lane</td>
<td>technical failure of the vehicle</td>
<td>traffic jam</td>
</tr>
<tr>
<td>• loss of load</td>
<td>flat tire</td>
<td>collision</td>
</tr>
<tr>
<td></td>
<td>run out of fuel</td>
<td>fire</td>
</tr>
<tr>
<td></td>
<td>overheating of breaks</td>
<td></td>
</tr>
<tr>
<td>4. Burning vehicle or load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• vehicle stops in the tunnel</td>
<td>defect on vehicle</td>
<td>complete stop of traffic</td>
</tr>
<tr>
<td></td>
<td>defect on the load</td>
<td>traffic jam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>collision</td>
</tr>
<tr>
<td></td>
<td></td>
<td>can aggregate to a big fire</td>
</tr>
<tr>
<td>5. Leaking of dangerous goods</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>collision</td>
<td>complete stop of traffic</td>
</tr>
<tr>
<td></td>
<td>fire</td>
<td>traffic jam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>collision</td>
</tr>
<tr>
<td></td>
<td></td>
<td>direct casualties</td>
</tr>
<tr>
<td>6. Fire in the tunnel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>burning trash</td>
<td>collisions</td>
</tr>
<tr>
<td></td>
<td>vandalism</td>
<td>traffic jams</td>
</tr>
<tr>
<td></td>
<td></td>
<td>direct casualties</td>
</tr>
<tr>
<td>7. maintenance works</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>unexpected situations</td>
<td>collisions</td>
</tr>
<tr>
<td></td>
<td>bi-directional traffic</td>
<td>traffic jams</td>
</tr>
</tbody>
</table>

Table 1-1: Accident situations in road tunnels, (source: Scenario’s tunnel incidenten, (Dutch) [3])
2 Risk assessment in tunnels

Risk assessment in tunnels takes three steps. First of all we have to find a way to determine safety. For instance is safety expressed in the number of fatalities or in money (2.1). Then we need to define a norm for safety and finally we need a model that can be used to calculate the risk level of a tunnel. In this chapter a description is given of two risk assessment methods (the scenario analysis (2.2) and the probabilistic approach (2.3).) and the safety norms used. Finally paragraph 2.4 explains the Present Value method. This method can is used to sum all costs that are made in different years during the economic lifespan to one year, taking into account the depreciation of money over time.

2.1 What is “safety”?

Safety first is a term heard throughout the world and translated into most languages, but what is safety? The following definitions of safety can be found:

- “Safety is the acceptable freedom from injury, damage, or loss of system availability” [14].
- “Safety is a compromise that optimises acceptable actions with a small amount of risk” [14]
- “Safety is the freedom from unacceptable risks” [15]

So safety is about (un)acceptable risks, but what is (un)acceptable and how do we define risk?

Risk can be represented in various ways. Below 4 views on risks are given [42].

1. risk is the probability of an undesirable event
2. risk is the consequence of the undesirable event
3. risk is the probability times the consequence of an undesirable event
4. risk is a function of the probability and the consequence of an undesirable event

The first two definitions can not be used because they focus solely on one side of the risk, which leads to inaccurate judgement of small probability accidents with large consequences or vice versa. The third definition however is a combination of both the probability and the consequences of accidents and is therefore often used (see paragraph 2.3.2, expected value). The fourth definition is the most common one. In fact the other three are special cases of this last one. The fourth definition enables the user to assign a weight to the consequences of the event. One can for instance emphasize the accidents with a small probability and a large consequence (see paragraph 2.3.2, characteristic value).

In order to come to the probabilities and consequences of tunnel accidents, an inventory is made of the events that can occur during the lifespan of the tunnel. Relevant questions are [16]:

- What can be a potential hazard?
- What will be the consequential damage?
- How many people could be in the vicinity?
- What injuries could be sustained?
These questions give an overview of the most important characteristics of various accident scenarios in tunnels:

- traffic situation; uni- or bi-directional tube (in the Netherlands all highway tunnels are uni-directional)
- location of a primary accident
- presence of a secondary accident
- presence of fire
- presence of toxic/ flammable goods
- number of people present in the tunnel at the time of the accident
- relative distance of the people in relation to the accident

Now that an inventory is made of the risks involved with a tunnel, an acceptable risk level is generally sought using three criteria: [17]

- Individual Risk (IR): minimising the individual risks of users
- Group Risk (GR): taking into account the social aversion of large scale accidents
- Economic Risk (ER): economic evaluation of safety measures

This means that consequences of tunnel accidents are expressed in two values: casualties and costs. A thorough safety concept should meet these three criteria and find an optimum.

2.2 Deterministic approach: scenario analyses

An approach used to investigate the influence of various safety measures is the deterministic approach. It is also used to give an indication of the level of safety of a tunnel. Of all possible scenarios that can occur in a tunnel a design scenario is defined. The selection of this scenario is done using experiences gained with existing tunnels. A problem is that the design scenario must be reasonable. This means that the probability of occurrence may not be too low, because that leads to an over design of the tunnel. The selection of the design scenario is therefore a tough debate between the various stakeholders involved in the conception of a tunnel. The design scenario covers the whole period between the first disturbance, the accident, and the development of the accident until everything returns to the normal situation again. This can be graphically presented using the so-called butterfly model (see Figure 2-1). First the circumstances leading to an accident are determined to get an idea what the situation is like at the time of an accident, this is represented on the left side in the form of a fault tree. Then the accident (shown in the middle) can develop in various ways, represented with an event tree on the right hand side. The design scenario is a combination of specific conditions leading to an accident combined with the maximum possible aggravation of the accident (an example is shown as the thick line).
2.2.1 Deterministic safety norm

Goal of this type of risk analysis is to examine the whole development and consequences of an accident. The development of the design scenario gives an idea about the level of self-help of the people present. Also the capacity of all safety equipment can be adjusted to this design scenario. The level of safety is often expressed in time, for instance the time needed

- for people to flee an emergency situation (an hour to reach medical assistance is often used as a maximum, also referred to as the “golden hour”)
- for the medical care to reach the accident (again golden hour)
- for the fire department to reach the accident (usually 15 minutes maximum)

An example of a design scenario for a tunnel is:

*During peak hour there is a bus (with 20) people present in the tunnel. There is a primary accident at the end of one of the tunnel tubes. There is a traffic jam as a result of this collision. Then a secondary accident occurs at the end of the traffic jam (100 cars) concerning a tanker loaded with flammable liquid. The flammable liquid leaks out (5 m$^3$) of the tanker.*

In this case the number of people trapped between the two accidents can be calculated. They have to flee the tunnel through the emergency exits in time. This scenario can thus be used to determine the level of self-help of the people present, the number of exits and the capacity of the fire department and medical care.

It is clear that the level of safety of a tunnel depends on the scenario that is used. Since there is no guideline on which design scenario is to be used for all tunnels there is no fixed safety norm. Therefore the selection of this design scenario is quite arbitrary and thus it is not possible to judge the level of safety with just one design scenario.
The German ADAC\textsuperscript{12} annually makes a deterministic survey comparing the level of safety of 30 European tunnels using a checklist of the facilities available \textsuperscript{[43]}\textsuperscript{13}. This seems to be a better way to judge the level of safety of a tunnel in a deterministic way. The checklist used in the survey included the following facilities:

- Traffic and traffic properties
- Escape paths
- Ventilation
- Tunnel configuration
- Communication facilities
- Emergency organisation

A copy of this survey is given in appendix B.1 (in German)

2.2.2 Advantages and disadvantages of the deterministic approach

The main advantage of the scenario analysis is that the design scenario gives a good insight in the influence of various safety measures (especially the performance of the fire department and medical care division. Besides it gives an idea about the way people are able to flee on their own (self-help). The design scenario is also used to set up an emergency plan.

A disadvantage of this method is that it cannot be used to define a safety level, because there is no bases for the choice of the design scenario. For instance if we should use this approach for our dyke system, we need to define a design scenario, in this case a maximum water level. For this scenario, one can suggest any water level. Though it is clear that we can not afford to heighten all the dykes in the Netherlands with up to 10 m. So the choice of the design scenario, depends on the probability of its occurrence. Thus we must compare the probability of occurrence of an event with the investments needed to avoid it. Then we can come to an optimum safety level.

2.3 Probabilistic approach: investigating all scenarios

The debate about which scenario must be chosen to evaluate safety in a deterministic approach can be given the correct position by using the more sophisticated probabilistic analysis. This method assigns probabilities to all possible scenarios. Furthermore each scenario is represented as an event tree with probabilities for all the various ways an accident can develop. An example of the first few branches of an event tree is given in Figure 2-2.

\textsuperscript{12} ADAC is a German car union (the largest car union in Europe)

\textsuperscript{13} The Wijkertunnel (tunnel under the North Sea Channel near Amsterdam) was assigned a third place with a score of 95 % (out of 100%).
The three risk measures as mentioned in paragraph 2.1 (Individual Risk, Group Risk and Economic Risk) can be calculated with the probabilistic approach. The Individual Risk and Group Risk are usually represented in an F-N curve (paragraph 2.3.1), while the Economic Risk is expressed in statistical data (paragraph 2.3.2).

### 2.3.1 F-N curves

The Individual Risk and Group Risk can be represented in the form of a F-N curve, which shows the relation between the frequency of occurrence (F) of an accident versus the expected number of fatalities (N). Figure 2-3 shows such a F-N plot. Note that both axes are logarithmic. Appendix E.2 gives the F-N curves as calculated for the three tunnel cases selected for this research.

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The model used for this research also distinguishes three types of accidents: (1) breakdown accidents: no collision, no material damage to the tunnel; (2) Only Material Damage accidents (UMS): accidents without injuries and (3) Injury accidents: accidents with casualties.
Accidents in tunnels can be divided into three categories:

- **normal accidents**; these accidents are no different from accidents that occur on the open road, so for instance a collision of two cars or between a car and a truck. They have a relatively high frequency, but low consequences. (mostly little material damage and sometimes very few casualties)

- **accidents involving jammed people**; these are accidents where people get stuck in the vehicle as a result of the accident and cannot flee on their own. They have to be freed by the fire department, which is more difficult in a tunnel environment than on the open road. Therefore it is assumed that the number of fatalities is slightly larger and the injuries are more serious in tunnels compared with the same accident on the open road.

- **calamities (splc-accidents)**; calamities occur with a very low probability, but with very serious consequences, especially in tunnels. One can think of an exploding tanker. These accidents are therefore called “small probability large consequence-accidents” or splc-accidents.

These three categories are visible in the F-N curve in Figure 2-3. The normal and extra accidents (Individual Risk) are located on the left side with relatively high frequencies and low consequences. The splc-accidents (Group Risk) are located on the right hand side with small probabilities and large consequences.

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15 This F-N is the result of calculations made with the Tunprim model [50], which is developed at the Ministry of Transport, see paragraph 6.2.1 for the characteristics of this model and appendix D.1 for the event tree of this model. The parameters used for all the cases are given in appendix E.2

16 A risk analysis on the Westerschelde tunnel [20] shows that the statistical expected value of people dying as a result of an splc-accident is about 560 times smaller than dying as a result of the two other causes.
2.3.2 Expressing risk in statistical values (EV, sigma and CV)

The results of a probabilistic calculation can also be expressed in statistical data like the Expected Value, the standard deviation and the Characteristic Value.

**Expected Value**

As mentioned in paragraph 2.1, risk can be expressed as the sum of all probabilities of all accidents times their consequences, or in other words: the Expected Value (EV)\(^1\). (risk definition 3)

\[
EV = \sum_i (\text{probability} \times \text{consequence})
\]

Since the Expected Value (EV) is the sum of the probability times the consequences of all different scenarios, there is no distinction between a high probability times a low consequence and a low probability times a high consequence. Therefore the use of the Expected Value only is risk neutral.

Calculations of the EV made for the three cases under consideration in this investigation showed that the EV for the number of deaths is made up for more than 90 % out of the deaths due to normal accidents. The deaths due to the transport of hazardous materials and fires in tunnels (splc-accidents) only have a noticeable effect on the EV when very large amounts of hazardous materials are transported or when the tunnels are very long. This means that the EV depends largely on normal accidents and that the splc-accidents have only very limited influence (see appendix E.3). Thus safety measures aiming at fighting the scenario’s concerning splc-accidents are not visible in the EV.

**Standard deviation**

The standard deviation of the Expected Values gives information about the deviation of the EV. It is calculated as follows:

\[
\sigma_N^2 = \sum (\text{probability} \times (N - EV)^2)
\]

where:

- \(\sigma_N\) : standard deviation of the number of fatalities (N)
- N: Number of fatalities
- EV : Expected number of fatalities (N)

Figure 2-4 shows two normal distributions\(^2\) with the same expected value, but with a different deviation. It is clear that although the EV is the same for both distributions, the narrow distribution (number 1) is preferred to the one on with the large deviation (number 2), because the probability of the EV for distribution 1 is higher than the probability of the EV for distribution 2. This means that the probability of large scale accidents is higher for distribution 2 than for number 1. Therefore the standard deviation can be used to determine the risks of large scale incidents.

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\(^{1}\) This is the total area under the curved line in the F-N curve.

\(^{2}\) In reality the distribution of accidents will not be a normal distribution, it is only used here for demonstration purposes.
Figure 2-4: Two normal distributions with the same Expected Value, but with a different standard deviation.

**Characteristic Value**
A value that takes into consideration the social aversion of the public towards calamities is the Social Risk criterion or Characteristic Value. This criterion takes into account not only the EV, but also the deviation:

\[
CV = EV + k \cdot \sigma (N)
\]

where:
- CV: Characteristic Value
- k: number defining the probability of exceeding, for evaluation risks in tunnels, k is usually taken as 3\(^{19}\)

The Characteristic measure is risk averse, because it emphasises the accidents with a low probability and a large consequence (risk definition 4, paragraph 2.1). A graphic explanation of the Characteristic Value is given in Figure 2-5. The figure shows the relation between the probability of an accident versus the number of fatalities of that accident. The large arrow on the left represents no accident. Because the probability of an accident is very small, the arrow almost reaches “1”. However, accidents do occur and they are represented with the curve. On the left side are the normal accidents (with a relatively high frequency) and more to the right the splc-accidents with a low probability. As mentioned before, the normal accidents mainly determine the EV. However if we add three times the standard deviation of this EV, we get the Characteristic Value on the right, which emphasises the splc-accidents.

\(^{19}\) For a standard-normal probability density function and \(k = 3\) the probability of exceeding is 0,1 % per year [50].
2.3.3 Probabilistic safety norm
At present there is no decision framework and thus no legal safety norm for tunnels, there are only guidelines. These guidelines deal with the social aversion to large accidents (Group Risk as described in paragraph 2.1). They are derived from the guidelines that are used for the evaluation of risks associated with industrial activities like chemical plants or airports. These guidelines prescribe that with an increase of the number of fatalities with a factor 10, the probability must be 100 times lower. Though there is a difference between industrial safety and tunnel safety. Users of a tunnel experience an internal safety whereas living in the neighbourhood of an industrial plant is an example of external safety.

The main difference is that the users of a tunnel benefit from using it and can weigh their benefit against the increase of risks. People in the direct vicinity of an airport however are exposed to the external risk introduced by the airport, but do not necessarily benefit from it. This means that they are confronted with an increase of risk, but they don’t have a benefit to balance it. Therefore it is likely that the acceptable risk level for internal safety is higher than for external safety. So usually as a rough guideline the risk level for internal safety is defined as ten times the risk level acceptable for external safety.

The guidelines for internal and external risk level are presented in the F-N curve in Figure 2-3: Example of a F-N curve, for the Wijkertunnel.

2.3.4 Advantages and disadvantages of the probabilistic approach
The most important advantage of the probabilistic approach is that it takes into account all possible scenarios with their probabilities. The results can then be represented according to the level of risk one is willing to take; neutral or risk averse. This makes it possible to compare the safety situation of various tunnels.

Another favourable aspect is the way the risk level can be presented in the form of a FN-curve. The guideline for internal safety is used to evaluate whether a tunnel complies with the expectations of society (Group Risk). These figures thereby make safety visible.

Finally the probabilistic approach can be used for economic evaluation. When all the damage aspects are assigned monetary values (see paragraph 4.3), the total damage can be weighed against the investments\(^2\).

\(^2\) An economic evaluation is done when it is clear that the tunnel meets the Group Risk criterion.
On the other hand one must realise that there is little data available, which makes the estimation of the parameters used in a probabilistic model a difficult task. Tunnel safety can therefore become a tough debate. Even when the probabilistic design criteria are met, one can doubt the assumptions that were made during the calculations.

2.4 Present Value calculation method

The probabilistic approach is suitable for economic risk analysis, however there is a problem with comparing the various costs involved. Not all the costs are not made in the same year. Most of the investment costs are made before the opening of the tunnel, while the risk is spread over the economic lifespan of the tunnel. And since money depreciates over time, the depreciation of all costs has to be taken into account. This can be done using the Present Value, summing all costs over a certain period of time including the depreciation of money. All costs can then be expressed in a value corresponding with the value of the money in the base year. All costs in this investigation are expressed in euros of 2002 and the discount rate is taken at 4 %, which is according to the national guidelines [22,23].

The calculation of the Present Values is done using:

$$NPV_{30} = \sum \left( \frac{E_i}{(1+r)^{(X_i-X_0)}} \right)$$

where:
- $PV_{30}$: Present Value for a period of 30 years
- $X_0$: base year of calculation, taken as 2002
- $X_i$: year of investment/risk
- $E_i$: investment/risk cost in year $i$
- $r$: discount rate, here taken as 4 %
3 Safety measures applicable to tunnels

Now that the causes of accidents are investigated and the probabilistic method is chosen to evaluate the risk level, it is necessary to investigate the costs of safety measure applicable to tunnels. First of all an attempt is done to categorize all safety measures (3.1), followed by an overview of all safety measures (3.2). Then a selection is made of several measures (3.3) that are investigated for three tunnel cases in chapter 5. The effects of the safety measures on the safety level of a tunnel are described in 3.4. Finally the costs of these safety measures are estimated (3.5).

3.1 Introduction

There are several ways to categorize safety measures that are applicable to tunnels. A common approach is the so-called safety chain. This safety chain distinguishes 5 ways to improve safety. Table 3-1 shows this safety chain and an attempt to categorize safety measures applicable to tunnels to each category.

<table>
<thead>
<tr>
<th>measure</th>
<th>aim</th>
<th>example(s)</th>
<th>result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pro-action</td>
<td>• remove the structural causes of accidents</td>
<td>• no access of flammable goods</td>
<td>• no fires involving dangerous cargo</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• uni-directional tubes instead of bi-directional</td>
<td>• no head-on-collisions</td>
</tr>
<tr>
<td>Prevention</td>
<td>• reduce the frequency of accidents and limit, as much as possible, the effects in case of an accident</td>
<td>• avoiding a black hole</td>
<td>• decrease accident frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• construction of a shoulder</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• reducing the speed limit</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• fire resistant walls</td>
<td></td>
</tr>
<tr>
<td>Preparation</td>
<td>• deal with the accidents and provide assistance during emergencies</td>
<td>• fire extinguish facilities</td>
<td>• prevent escalation of the fire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ventilation</td>
<td>• keep people out of the area of influence</td>
</tr>
<tr>
<td>Mitigation</td>
<td>• fight the consequences of an accident</td>
<td>• medical care</td>
<td>• taking care of the injured people</td>
</tr>
<tr>
<td>After-care</td>
<td>• return to the normal situation as soon as possible.</td>
<td>• making replacement of equipment after damage more easy</td>
<td>• reduction of the time that the tunnel is out of use</td>
</tr>
</tbody>
</table>

Table 3-1: Examples of safety measures according to their role in the safety chain.

Although the safety chain seems a good and logic way to categorize safety measures, its use is limited. Usually a safety measure serves multiple purposes in different stages of the development of an accident and can therefore not be labelled as acting in only one of the phases used in the safety chain. For instance fire extinguish facilities can be described as repressive, because they are used to extinguish a fire, or preventive because they can prevent escalation.
of a fire. An attempt to present all possible safety measures according to their role in the safety chain is given in appendix C.1. However, it did not succeed.

It might be better to use not just one safety chain for the complete lifespan of the tunnel, but for everyone participating in the design, construction, and operation of the tunnel and its users to make their own safety chain. For instance, someone driving through a tunnel can consider the following safety measures: choose another route (pro-active), reduce his speed (preventive) or take a fire extinguisher in his car (preparation) etc. The same thing can be done for every other participant in the process. Though the problem with the fire extinguish facilities (serving two purposes in different stages of the safety chain) is not solved.

Another solution is to categorize safety measures relative to the time path of the realization of the tunnel: plan, design, construction and operation [36]. During the construction of a tunnel, safety can be influenced by the material and temporary constructions; the artefacts. Besides, the organisation, and a route or location that are needed also influence the level of safety. Deviations that may occur during these stages can be minimised on the levels medical care and fire department.

Finally a division can be made into measures aiming at reducing the probability of an accident or reducing the consequences of the accident. Of the safety measures aiming at reducing the consequences of accidents, one can distinguish safety measures that aim to save people involved in the accident and measures that aim specifically at saving the tunnel structure itself. Of course these goals do often coincide, but not necessarily. (e.g. a sprinkler installation only aims at saving the tunnel structure).

Since no division of safety measures was considered satisfactory, another division was made for this investigation, following the three different departments of the Ministry of Transport involved in the development and exploitation of a tunnel:

- design of the structure (structural measures)
- design and maintenance of the electrical installations (installation measures)
- exploitation of the tunnel and its traffic rules (traffic management)  

This division was chosen because the information about the costs and effects of safety measures under consideration in this investigation is also available at these three departments.

In chapter 1 it was concluded that the influence of the Ministry of Transport on the probabilities of accidents is limited to the road (design of the tunnel); the vehicle (exclusion of dangerous goods) and the driver and traffic (traffic management).

Adjustments to the tunnel design (road) are considered structural measures and the regulation about the transport of dangerous goods and the traffic rules (vehicle, driver and traffic) are in the category of traffic management.

Since this report is written for the Ministry of Transport, it takes into account those areas that are under their direct supervision and within their budget. One should realize that safety measures in the area of medical care and after care

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21 In cooperation with the Ministry of Housing, Spatial Planning and Environment and the Ministry of Justice
are not investigated here, but should be included in a complete economic optimisation.

3.2 Overview of applicable measures to improve safety in tunnels

Here the three categories of safety measures are discussed and some examples are given. A complete overview of applicable safety measures is given in appendix C.2.

3.2.1 Structural measures

Structural measures are incorporated in the design of a tunnel. They comprise mainly pro-active and preventive measures. Some examples are:

- Construction of uni- or bi-directional tubes (frontal collisions)
- A well-designed alignment (avoid curves, steep hills etc.).
- A well-designed tunnel geometry and lighting system that avoids entering a black hole.
- Construction of a (hard) shoulder
- Emergency niches
- Cross connections and escape routes (refuge areas, escape tunnels, pressurized emergency exits)
- Accessibility by the emergency crews
- Fire resistant tunnel lining

3.2.2 Electrical installations

Another group of safety measures is the electrical installations in the tunnel. Their aim is usually to increase early detection of accidents and prevent escalation. The following measures can be considered:

- Detection systems (fire detection, height detection, traffic incident detection, vehicle identification system, Speed Detection System (SDS), CO and/or visibility measuring)
- Fire extinguish equipment
- Ventilating systems
- Communication systems (Closed Circuit Television system (CCTV) / video surveillance, High Frequency installation (HF), emergency telephones, intercom / speaker system)
- Lighting of the tunnel
- Emergency energy supply / emergency lighting

3.2.3 Management measures

Finally safety can also be optimised with measures taken at an organizational level. One can think of:

- Traffic control systems (traffic regulations, speed limits, no overtaking, dosing traffic on ramps, regulations governing the transport of hazardous materials (introduction of a time frame for this type of transport or through dedicated tubes, escort convoys of dangerous goods or limiting the quantities of permitted products)
- Safety measures that aim to improve the ability of people to flee an emergency situation on their own (self-help), such as:
  - information and rules of behaviour for travellers (e.g. radio announcements)
  - making people alert to the dangers of tunnel accidents (e.g. show movies on TV in the region, give special attention to tunnels during driving lessons etc.)
- A well designed control and managing philosophy
3.3 Selection of safety measures

Of all the safety measures mentioned in appendix C.2, it is not always possible to assign the effect on the level of safety to one single measure. Since the goal of this research is to find a correlation between the investments on safety and the gain in safety, it must be clear what the effect of the investigated safety measures is. Therefore a selection is made from all the applicable safety measures for this investigation.

Safety measures considered to be beyond the scope of this investigation

First of all some safety measures are considered to be beyond the scope of the project. They are summarised in Table 3-2 below.

<table>
<thead>
<tr>
<th>Type of measure</th>
<th>Measure</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural measures</td>
<td>• constructing bi-directional tubes</td>
<td>• all highway tunnels in the Netherlands are uni-directional(^{22})</td>
</tr>
<tr>
<td></td>
<td>• emergency niches</td>
<td>• never used in the Netherlands</td>
</tr>
<tr>
<td>Electrical installations</td>
<td>• dynamic compartments</td>
<td>• these techniques are not fully developed yet</td>
</tr>
<tr>
<td>Management measures</td>
<td>• equip all traffic with fire extinguishers or exclusion of all “LPG” tankers</td>
<td>• these measures must be done nation wide and there is no sign that this will happen in the near future.</td>
</tr>
<tr>
<td></td>
<td>• transport of dangerous goods trough dedicated tubes or alternative routing of dangerous goods</td>
<td>• this does not solve the problem, but moves it. Besides there is a movement towards less restrictions for transport of dangerous goods on the Dutch highway system.</td>
</tr>
</tbody>
</table>

Table 3-2: Safety measures that are considered to be beyond the scope of the project.

Measures that are assumed to be applied in every design

Then there are measures that are assumed to be taken into account in every design in Dutch tunnels, because they are mentioned in the design guidelines for tunnels in the Netherlands \([4]\). One can think of:

- alignment (avoid curves, steep hills etc.)
- tunnel geometry (avoid black holes).
- shift the entrances of two tubes relatively (avoid smoke entering “safe tube”)
- use impermeable asphalt as road surface (reducing the effect of a pool fire)
- flame traps (prevent spreading of fire).
- situating the electricity equipment at a non-vulnerable place
- over-pressure relief valves
- use of escape routes
- optimisation of accessibility of the emergency crews

\(^{22}\) A bi-directional tunnel demands a complete different safety concept (there is no “safe tube”, other ventilation regime etc.) Therefore it is not possible to compare this type of tunnel, with the uni-directional alternatives.
- reflecting tunnel lining (improved visibility)

These measures are left out of the research because it is assumed that the three tunnels investigated are designed according to the Dutch guidelines for tunnels.

Safety measures that can be taken into consideration

Of the measures that can be taken into account, a division is made into measures that are common in Dutch tunnels and additional measures that can be evaluated (Table 3-3).

<table>
<thead>
<tr>
<th>Type of measure</th>
<th>Common in Dutch tunnels</th>
<th>Additional measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Measures</td>
<td>• fire resistant tunnel lining</td>
<td>• change distance between the cross connections[^23]</td>
</tr>
<tr>
<td></td>
<td>• extinguish facilities</td>
<td>• construction of a hard shoulder</td>
</tr>
<tr>
<td>Electrical installations</td>
<td>• detection systems</td>
<td>• sprinkler installation</td>
</tr>
<tr>
<td></td>
<td>• fire extinguish equipment</td>
<td>• extend the Speed Detection System (SDS) beyond the tunnel exits</td>
</tr>
<tr>
<td></td>
<td>• ventilating systems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• communication systems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• emergency energy supply / emergency lighting</td>
<td></td>
</tr>
<tr>
<td>Traffic Management</td>
<td>• regulations for the transport of hazardous materials</td>
<td>• escort convoys of dangerous goods and separate them from the rest of the traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• introducing a time frame for transport with dangerous goods and separate them from the rest of the traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• traffic regulations (speed limits, no overtaking, exclusion of dangerous goods)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• minimum distance between vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• information for travellers (radio announcements)</td>
</tr>
</tbody>
</table>

Table 3-3: Safety measures common in Dutch highway tunnels and possible additional measures.

3.4 Effects of safety measures

Research was done on the effects of the safety measures given in Table 3-3 in relation to the safety level of a tunnel. The safety level was investigated using the probabilistic Tunprim model. This model, under development at the Centre for Tunnel Safety at the Ministry of Transport[^24] [30,50] evaluates the Group

[^23]: For immersed tunnels and land tunnels the mutual distance normally is 100 m, though for bored tunnels there is a tough debate, because these cross connections are very costly.

[^24]: The version dating from June 13th 2002 was used. A schematic overview of the event tree used in the model is given in appendix D.1. The main characteristics and some comments on the model are given in appendix D.2.
3.4.1 Structural measures

Construction of a hard shoulder (nr. 3)
A shoulder in a tunnel decreases the pressure experienced by the driver because it reduces the negative feelings related to the closed configuration of the tunnel. It is found in several studies that the accident frequencies are lower in tunnels where a shoulder is present. A German study on shoulders [5] shows an accidents reduction of 20% in tunnels with a shoulder and even 31% for the rest of the highway system. A Dutch study found an increase/decrease of the accident frequency of 15% [33]. This number was used in this study. Furthermore a shoulder has a positive influence on the number of traffic jams. It is assumed that when a shoulder is present 100% of the breakdown vehicles reach the shoulder before they stop [33]. For only material damage accidents (UMS) and injury accidents it reduces the chance of the built up of a traffic jam behind it. Appendix C.6.1 gives the probabilities of blockage of a traffic lane as a result of an accident for 2, 3 and 4 traffic lanes, with and without a shoulder.

Cross connections (nr. 4 and 5)
The mutual distance between cross connections is relevant for the injuries and fatalities resulting from “split-accidents”. The Tunprim model calculates an area of influence for every accident scenario. This distance is used to determine the amount of casualties. The maximum area of influence is assumed to be equal to the distance between the cross connections. Reducing the mutual distance of cross connections therefore has a relation to the number of casualties. However, doubling the number of cross connections will not automatically lead to a fixed reduction percentage of casualties. The reduction in casualties depends on the scenarios that occur in the tunnel, the area of influence as a result of various accidents and the number of people “trapped in the tunnel”. However, in general the longer the distance between cross connections, the more difficult it is to flee the emergency situation and thus more casualties can be expected.

Heat resistant lining (nr. 6)
A huge fire can harm the strength of the tunnel structure and may cause the collapse of the tunnel. A heat resistant lining is applied to reduce the temperature at the concrete surface of the tunnel lining and thus prevents this collapse. It is especially useful for the scenarios that involve large fires. Besides it reduces the diffusion of heat through the rest of the tunnel and thereby decreases the area of influence of these scenarios.

3.4.2 Installations and equipment

Fire equipment (nr. 7)
If fire extinguish facilities are available in a tunnel, it is assumed in the Tunprim model that 25% of all fires caused by breakdown accidents of cars and 10% of the breakdown accidents of trucks and busses are extinguished. For the injury accidents and UMS accidents it is assumed that none of them are extinguished [30]. Removing the fire extinguish facilities will thus result in 25% more (un-extinguished) car fires and 10% more truck and bus fires.
Ventilation (nr. 8)

A ventilation system is used in normal situations to remove heat and exhaust gasses from the tunnel. In case of an emergency, a ventilation system is used to direct the by-products of fires, in other words to separate the heat in the tunnel from the people present. It can thus be used to control and limit the area of influence of an accident. If there is no ventilation system in the tunnel, smoke, heat and (toxic) gasses spread in two directions from the fire. In Dutch unidirectional tunnels, the airflow generated by ventilators is parallel to the traffic flow. This ventilation regime enables people that are stuck behind the fire to flee on foot, free from heat and toxic gasses. Though this means that people in front of the accident are confronted with these gasses, but they are expected to make their way out of the tunnel by car.

Sprinkler (nr. 9)

Sprinkler systems are highly regarded by fire protection professionals and fire departments because of their long successful history in (office) buildings25. First of all, fires in buildings differ from fires in tunnels, because the fire loads in tunnels are much higher (for instance compare a burning desk with a burning truck). Besides the quantity of the material available during the fire differs (in office buildings mainly a few paper versus a few vehicles with fuel in tunnels). At present there is little experience with using sprinklers in tunnels26. Here is a summary of the advantages and disadvantages found in literature. Though, one must realize that this discussion is highly theoretical and not much scientific data is available. These arguments are used for the schematisations made for the evaluation of a sprinkler system in this investigation.

Advantages

The main advantages of sprinkler systems are:

- Sprinklers can prevent the spread of fire to other vehicles. This is important when the burning vehicle is in a traffic jam [38].
- A sprinkler system can gain time for the fire department to enter the tunnel and save people that can not leave the tunnel themselves, for instance because they are jammed or disabled [38].
- Automatic fire suppression systems may be of benefit in reducing the damage costs of vehicle (and load) and can prevent structural damage to a tunnel. Ultimately a sprinkler system may prevent a collapse of the tunnel during a huge fire [39].
- If the sprinkler has a sufficient cooling capacity to extinguish or minimize a fire a hot BLEVE27 can be prevented [38].

Disadvantages:

However there are also some disadvantages concerning the use of sprinklers:

- The efficiency in reducing loss of life in the event of a hazardous material tunnel fire is doubted. The fire will probably be fully involved before the suppression systems are able to activate. There will be a time lag between fire ignition and fire detection and another time lag while the suppression system pumps are started, valves are opened, and the delivery system piping is filled with water [6]. People who are

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25 It has been claimed that no life has ever been lost in a sprinklered building [6]
26 No European country currently uses sprinklers on a regular basis. In Japan, sprinklers are only used in long or heavily trafficked tunnels and in the USA only 3 tunnels have sprinklers.
27 A BLEVE (Boiling Liquid Expanding Vapour Explosion) can occur when a fire underneath a tanker heats the gas until the pressure is more than the tanker can bear. Then the tanker will explode. If a fire underneath a tanker is minimised or extinguished, a BLEVE can be prevented.
able to flee this emergency situation are assumed to have left before
the sprinkler system starts operating.

- Tunnels are generally very long and narrow, so heat will not be
  localized above the fire only. A dangerously large hazardous material
  fire will grow and spread hot combustion products far from its origin
  before sprinkler heads open. An inordinately large flow of water would
  be required to deliver an effective spray through all the possibly open
  heads to assure application on the fire itself [6].

- A thin spray of water onto a hot fire will produce large quantities of
  superheated steam without materially suppressing the fire. This steam
  is found to be more damaging than the comparatively well-behaved
  smoke. Spray away from the fire is not only a waste of water, it will
  also tend to disturb the stratification of smoke and lifesaving fresh air
  that may have been established [6]. Finally it may decrease the
  visibility in the tunnel.

- Automatic detection of the sprinklers by active detectors has to be
  delayed until all traffic is halted, since even a light spray of water will
  catch drivers unaware. The spray of a sprinkler is more than the wipers
  can clear (even if they are ON). Besides these huge amounts of water
  will make the road surface slippery [6].

- Small fires are usually under vehicles, or inside passenger or engine
  compartments designed to be waterproof from above; overhead
  sprinklers are thus not effective.

- Unless quickly extinguished at their source, flammable liquid fires can
  continue to burn atop of the sprinkler outwash. Drains, and sewer
  capacity must be designed to dispose huge quantities of this burning
  mixture [6]. If pool fires with flammable liquids have to be
  extinguished, a chemical additive\(^{28}\) can be used in the water to
  prevent a fire atop of the water.

- The sprinkler and detection system must have a very high degree of
  performance\(^{29}\). Failure when the system is needed must be very little,
  since these occasions are very rare. On the other hand, the sprinkler
  system must not activate without a fire, because then it will endanger
  the people present in the tunnel.

- A problem with the detection systems used to activate a sprinkler
  system is that the demands on the sensitivity are very high. On one
  hand the detection system must be extremely sensitive (it must detect
  and locate a burning vehicle that may still be moving), otherwise the
  wrong section of the system may be used. On the other hand it may
  not be too sensitive, while that may cause a false alarm (for instance
  the exhaust pipe of a truck is usually on top of the truck. In a traffic
  jam, the heat from the exhaust pipe may be interpreted as a fire
  incorrectly)

**Conclusion**
Summarizing the advantages and disadvantages, it can be stated that there is
little scientific data and experience with sprinklers in tunnels. Though there are
indications that the sprinkler system can be useful to reduce the aggravation of
some scenarios. It may prevent a BLEVE resulting in a collapse of the tunnel; it
can reduce pool fires, when additives are used and it can gain time for the
emergency crews to enter the tunnel. However there are no indications that
more lives can be saved. On the contrary there are some signs that the
sprinkler system may endanger people in the direct vicinity of the huge fire.

\(^{28}\) usually a chemical is used called AFFF (Aqueous Film Forming Foam)

\(^{29}\) At the moment the figures for accidental discharge is 1 in 500.000 sprinkler heads per year [46]
Another serious issue is the detection systems that are needed for a sprinkler system. There are contradicting and tough demands. On one hand the reaction time must be very little, thus preferably automatic [38]. On the other, people close to the fire must have the opportunity to flee before the system gets activated. Besides it must be very accurate and failsafe! At the moment none of the detection systems can comply with these demands.

While there is little data (sometimes contradicting) on sprinklers more research is needed. For this research some assumptions were made for the efficiency of a sprinkler system. They are quite optimistic, while this investigation is a first rough investigation on the cost efficiency of safety measures. Since the investment costs of a sprinkler system are considerable, a conservative approach would immediately result in a cost inefficient judgement. With this “optimistic” approach, one can see whether a sprinkler system with a very high degree of performance might be cost effective. Then more research can be done to try and take away the disadvantages mentioned above. The following assumptions were made for this research:

- The sprinkler system aims at reducing the risk resulting from accidents and **not** at saving lives.
- Using a sprinkler system will not result in more casualties
- A sprinkler system can prevent 90% of the BLEVE’s [a]
- The material damage to the tunnel as a result of scenarios involving fires with slightly flammable goods or dangerous goods will be half as much if a sprinkler installation is applied (see also appendix D.3).

**Speed Detection Systems (SDS) (nr. 10)**

A Speed Detection System is a series of electric loops in the road surface. It can detect vehicles stopping in the tunnel, indicating that there is an accident. It is therefore usually used as an early warning that something other than normal is happening. Nowadays Speed Detection Systems are only applied within the Dutch tunnels for this purpose. But the system can also be useful to detect the built up of a traffic jam behind the tunnel exit, when it is extended outside the tunnel. Then it can be used to prevent a scenario with a traffic jam in the tunnel and an accident at the end of this traffic jam. This is one of the worst scenarios in a tunnel, because when the ventilation system is turned on after an accident with a fire, the people in front of the accident are confronted with all products of fire (smoke, heat, toxic gasses) and can only leave the tunnel on foot. This means that a lot of people are in a vulnerable position, trapped between two accidents. Extending the SDS behind the exit of the tunnel with only a hundred meters can detect a built up of a traffic jam and warn the tunnel operator. The tunnel operator can then close of the tunnel entrance to prevent a built up of a traffic jam towards the tunnel exit, and thus eliminate these scenarios.

**3.4.3 Regulatory measures**

**Escort of the transport of dangerous cargo (nr. 11)**

Other severe scenarios concern accidents with trucks loaded with dangerous cargo (flammable or toxic). These accidents have a low probability, but with severe consequences, especially when a lot of people are present in the tunnel. Therefore escorting such type of transport and separate them form the rest of the traffic can be an option.

First of all, when other traffic is not permitted in the tunnel during these convoys of dangerous goods, the number of people present in the event of an accident drops considerably. Besides, while no other traffic is present, the
accident frequency of the trucks is estimated to be 100 to 1000 times lower when dangerous cargo is transported in a convoy [a]. Moreover the probability of a fire is estimated to decrease with 25 % [34] and the chance of a leak of the cargo is estimated to drop 40 % [34].

In the model used in this investigation it is not (yet) possible to distinguish different accident frequencies for various types of transports. So estimations of the damage under a regime of transporting dangerous goods in convoys, were made using a combination of two runs of the model. The number of fatalities and injuries was calculated in a normal situation without dangerous goods. The calculations on material damage were done by multiplying all accident probabilities of the scenarios involving dangerous goods with 0,01 (1/100 of the original accident frequency); the scenarios with fire with 0,75 (25 % reduction of fires) and the scenarios with a leak with 0,60 (40 % less leakages).

Introducing rules that forbid overtaking in the tunnel (nr. 12)

Research on banning overtaking on certain parts of a highway [35] do not clearly show a decrease in the number of accidents. Therefore this safety measure was left out of this research.  

Reduction of the speed limit with 20 km/h (nr. 12)

It can be expected that when the speed limit is reduced, the number of accidents will drop and it will reduce the consequences of accidents. A lot of research is done on the effect of speed limits on highways, though the influence found varies considerably. Besides, most investigations focus solely on the influence on the probability of accidents. Studies show a variation of the influence of a speed limit on the probability of an accident of –10 % [36], -20% [65] to – 40 % [33]. For this research it is assumed that a speed reduction of 20 km/hour will reduce the accident frequency with 20 %. While no data was found on the effect on the consequences of accidents, it is assumed that the number of casualties per accident is the same (conservative approach).

Improving the use of the escape routes (nr.13)

Research on the influence of the use of escape routes was not found, so an assumption was made that by radio announcements and frequent exercises it is possible to improve the use of escape routes. In every scenario involving people that are trapped, it is assumed that 10 % more of them are able to flee. For instance the chance of fleeing a fire following an injury accident with a bus is set at 40 % in the original model. This percentage was increased to 44 %.

Improving the use of the extinguish facilities available to tunnel users (nr. 14)

No research was found on the influence of the use of fire extinguish facilities by the users of tunnels on the safety level of tunnels. Therefore it is assumed that improving the use of this equipment, by giving regular instructions and radio announcements, will increase the percentage of fires that are extinguished with 10 %.

For this research it is assumed that 35 % of the fires from breakdown accidents of cars and 20 % of fire from trucks and busses are extinguished (instead of 25 % and 10 %).

Minimum distance between vehicles (nr. 15)

In other countries in Europe one may find stripes on the road surface indicating that it is the minimum distance that must be kept to the vehicle in front. The goal is to decrease the frequency of head-tail collisions. For this research it was estimated that the number of accidents drops with 10 % as a result of this measure.

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30 Though it does have positive effects on the traffic flow (4-5 % increase of the road capacity).
3.5 The costs of safety measures

The costs of safety equipment are related to the construction of the tunnel (paragraph 3.5.1), the electrical installations (paragraph 3.5.2), and the traffic management solutions (paragraph 3.5.3). While not all these costs are not made at the same time, the Present Value method is used to compare the costs related to all safety measures over the whole economic lifespan of the tunnel, taking into account the depreciation of money over time (paragraph 3.5.4). They are discussed in this paragraph. A full overview of the costs of safety measures is given in appendix C.3.

3.5.1 Construction costs (structural measures)

Differences in construction types of tunnels have a large influence on the costs of safety measures. In general the costs are relatively high for a bored tunnel and of the same magnitude for immersed and land tunnels. The following aspects contribute to the large differences in costs for safety equipment for different tunnel constructions.

Distance between tubes

The tubes in immersed and land tunnels are only separated by a small equipment tunnel, which is also used for emergency situations. The tubes of a bored tunnel however, usually have a mutual distance of 10-15 meters. This has a large influence on the costs of the escape routes. A door in the tunnel wall of an immersed or land tunnel is enough to reach a safe place (cable channel or safe tube). In bored tunnels however, a special tunnel has to be constructed to inter-connect the two tubes. These connections are very costly.

Heat resistant lining

The stronger concrete generally used in bored tunnels is more vulnerable to spalling than the low strength concrete used in immersed and land tunnels. Therefore a thicker heat resistant lining is necessary. Research showed that the Promatec lining which is normally applied in tunnels is not suitable for this purpose. So instead of a Promatec lining, a shotcrete lining is used in bored tunnels, which is more costly.

Costs of enlarging the tunnel diameter for a shoulder or escape path in the tube

The costs for a bored tunnel increase roughly linear with the increase of the cross section of the tube. This means that adding a shoulder or an escape route along the traffic lanes is very costly. For immersed and land tunnels the costs related to the construction of a shoulder are considerably lower (approximately 15% more).

Shape

The cross sections of immersed and land tunnels are square while for bored tunnels they are round. While maintenance vehicles in the Netherlands are usually equipped for square tunnels, they have to be adapted before the can be used in a bored tunnel. Besides cross sections in immersed and land tunnels do not have to be equal over the total length of the tunnel contrary to the bored tunnel. This has an effect on the space available in a cross section to adjust safety equipment. For instance, in land tunnels it is common to increase the cross section of the tube at the places where ventilation equipment is adjusted.

31 For this study the costs of a shoulder in the Bored tunnel, Immersed tunnel and Land tunnel were calculated to be respectively 40, 20 and 7.5 thousand Euro per meter tunnel.
3.5.2 Installation costs (installation measures)
The costs of safety equipment comprise a base part and a variable part according to the length of a tunnel. This means costs increase with increasing length, but not linear. The ratio between basic costs and variable cost also differs for various installations. In general there are no large differences in the investment costs of installations according to the tunnel construction type.

Inspection and maintenance costs of electrical installations
In most tunnels in the Netherlands maintenance on the electrical installation is carried out once every two weeks. During maintenance one of the tubes is closed. The tunnel and its walls are cleaned, the installations are checked and every year half of the light bulbs are replaced. The costs of this maintenance are not divided into several categories, but taken as a whole. Since the total inspection costs are relatively low and only relate to the tunnel itself or installations that are not considered individually in this research, these costs are left out (see appendix C.4).

Renovation costs
An investigation on renovation costs [p] revealed which installations need to be renovated within the selected lifespan of 30 years. Most of these renovation costs are very low and can therefore be neglected (see appendix C.4).

However, the renovation costs related to the following installations that enhance safety in tunnels are of interest:
- camera’s
- light armatures
- fire extinguish equipment
- ventilation (renovation)
They are taken into account in the Present Value of the total investment of these safety measures. Their costs are given in appendix C.4.

3.5.3 Costs of traffic management solutions
Besides the investment costs related to the introduction of some traffic management solutions (e.g. traffic signs), there are also yearly costs (e.g. law enforcement). Their costs are given in appendix C.3.3.

3.5.4 Summary of the costs of safety measures applicable to tunnels
The costs of safety equipment comprise investment costs, renovation costs and yearly costs related to inspection and operation. These are cost are made in different years and are compared by expressing them in a Present Value.

32 The economic lifespan is set at 30 years conform the recommendations in the guidelines for economic evaluation of infrastructure [22,23]
A difficulty in comparing the investment and renovation costs of safety measures for several tunnels is that the costs found in literature do not always include the same aspects. Investment costs estimations at the Ministry of Transport are made using the following categories [37].

- direct costs (material, resources)
- indirect costs
  - engineering (incl. tender)
  - construction (manpower, quality control, permits, operation)
  - overhead (revenues, interest, unforeseen)
- tax (VAT)\(^3\).

For this investigation the same pattern was used. Where only the direct costs were mentioned in the estimations of safety equipment, it is assumed that the indirect costs and VAT amount to 50% of the direct costs\(^3\).

Another aspect is the base year used in the estimations. All cost estimations were made in different years and thus use a different base year.

For this research all costs are brought to the level of 2002, are expressed in euros and include VAT.

Finally all costs related to tunnel safety measures (construction, installation, renovation and operation) are summed over the economic lifespan of the project and are presented in a Present Value. Figure 3-1 gives an example of a calculation of the Present Value of the costs of safety measures for an imaginary tunnel. It represents how the costs made in different years can be brought to one base year and expressed in a Present Value.

Appendix C.3 gives an overview of the costs for safety measures as they were found for the three cases used for this research. Appendix C.5 gives their Present Values\(^3\).

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33 In Dutch VAT is called BTW, a tax of 19% on top of the total costs.
34 This is the average found in cost estimations of the Bored tunnel and Immersed tunnel.
35 Some of the costs found for the Bored tunnel case may be higher than the market prices, because it was the first bored tunnel in the Netherlands. Moreover the discussion about the safety level was parallel to the construction of the tunnel. This resulted in extra work for the contractor (e.g. the number of cross-connections doubled), which is often done above market prices.
4 Consequences of tunnel accidents

4.1 Introduction

The risk of tunnel accidents can be calculated as the sum of the probability times the economic consequences of all scenarios. This means that all consequences of tunnel accidents have to be expressed in monetary values. First of all the number of injuries and fatalities is has to be calculated (paragraph 4.2). Then a monetary value is assigned to these casualties. Together with the calculated material risk they are the direct risk related to accidents in tunnels (paragraph 4.3). Next to these costs are the indirect costs of delay caused by accidents (paragraph 4.5).

4.2 Expected fatalities and injuries from accidents in tunnels

4.2.1 Expected number of fatalities

The expected number of fatalities for the three cases is calculated with the Tunprim model, which is under development at the Centre for Tunnel Safety at the Ministry of Transport\(^{36}\). This is a probabilistic model that evaluates the Group Risk level of a tunnel. The event tree of the model gives an overview of all possible scenarios in the tunnel. An amount of fatalities is then assigned to all the different accidents. A schematic overview of the event tree used in the model is given in appendix D.1.

4.2.2 Expected number of injuries

Injuries were not included in the available version of Tunprim. Therefore this category was added to the model using the same approach as was used to estimate the number of fatalities. An amount of injuries was assigned to all accident types. The number of injuries form tunnel accidents is roughly 10 times higher than the number of fatalities.

4.3 Direct costs of tunnel accidents

4.3.1 Fatalities, The value of a human life

Although there is an ethical problem in valuating the human life, we cannot escape it, since the safety budgets are always limited. Safety therefore is an economic issue and thus a monetary value is usually assigned to the human life to investigate the cost effectiveness of safety measures. Literature shows that there are several ways to human life valuation.

Human Capital Approach (HCA):
The human capital approach is based on the discounted present value of the victim’s future output (income) that is foregone due to his premature death\[^{11}\]. In the case of individuals whose services are not marketed (such as house person), a correction can be made for the value of their services. An allowance is then added for other effects such as damage, police and medical costs, etc. In some countries a more or less arbitrary amount is then added for the “pain, grief and suffering” of the victim’s relatives and friends.
The major objection to this approach is that most people do not value their life for its contribution to output, but rather because it has intrinsic value to them.

\[^{36}\] The version dating from June 13th 2002 was used.
So this approach does not provide accurate measurement of the parameter targeted. Instead it focuses on estimated production capacity.

**Willingness To Pay (WTP)**
This approach is based on the trade off people make between risk and money. How much are people willing to pay to reduce the risk of a premature death? [11]. It estimates the value that humans attach to life by means of surveys that aim to determine the amount of money that individuals are prepared to pay to reduce the risk of loss of life or injury. This method investigates the injuries that are borne by individuals and not the losses borne more widely by society. Therefore losses for medical care, public costs and net productive losses37 are added. The added components are only a small proportion of the total socio-economic costs of casualties.

A disadvantage is that filling in a survey about this topic is quite hypothetical to a lot of people. This can be the reason that this approach usually yields higher values than the human capital approach.

**Value of Statistical Life (VSL)**
The willingness to pay for one individual is often transferred into the Value of a Statistical Life, which expresses the sum of the WTP over a large group of people. For example, workers facing an annual occupational-fatality risk of 3 in 10,000 receive about $500 more in annual wages than workers with jobs in which the risk is only 2 in 10,000. This means that the 10,000 people are willing to offer $500 dollar each of their income to save one expected statistical death among them. The Value of this Statistical Life thereby yields $ 5 million [24]. Disadvantages of this method are that the workers in these (high risk) jobs are generally healthy, male and young and may have a different attitude towards safety than the average person. Secondly the people accepting these jobs are risk taking and not risk averse.

**Implied life value**
The implied life value is defined as the estimated Costs of Saving an eXtra statistical live (CSX) [25]. It measures the cost-effectiveness of interventions aimed at reducing the probability of premature death. An example of the costs of life saving methods in various fields can be found in (appendix D.5). The problem with this method is that it shows a large deviation in the costs involved in different life saving interventions. Furthermore it gives the marginal costs per human life, which means that the CSX may already be quite high, but still the total investment may be under the optimal investment.

An interesting question is whether the large variation in society’s investments in life-saving interventions reflects the public opinion or not. There is some empirical evidence that this is not the case. The public seems to support a variation with a factor two or three, but no more [26,27].

In a study on politicians [28] it was found that the risk reduction they desire largely depends on their beliefs about the public’s risk perception, more than by their own risk perception. This finding strongly supports the idea that it is important to study public opinion on investments in lifesaving interventions.

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37 the difference between the average value of lost production (HCA) and the average value of lost consumption by the individual at risk.
Conclusion
Of the different approaches to validate the loss of life, the Willingness To Pay / Value of Statistical Life method is preferred. Although economists have a lot of experience with the human capital approach, the European Conference of Ministers of Transport Round Table concluded that opting for this approach is not conceptually sound because it focuses on the wrong parameter [31]. Instead the WTP method is less commonly used, it focuses on the correct parameter. The Round Table suggested that inaccurate measurement of the correct parameter (WTP) is preferable to accurate measurement of a non-relevant concept (Human Capital Approach) [11]. The Implied Value method cannot be used because of the large deviation in its values.

4.3.2 Injuries, valuation of non-fatal injuries
Using the WTP method for valuing the costs of injuries has the difficulty that injuries have a great variety. Even a category like “serious injury” covers a wide range of injury conditions. Therefore the costs for injuries were estimated using statistical data [32, 44]. A division is made in people who need hospital treatment and people who only need first aid. The table below (Table 4-1) gives a summary of the costs related to fatalities and injuries of accidents on highways in the Netherlands. For this research the costs of injuries per registered injury is taken (and not of the real injuries), because the injury frequencies in the Tunprim model are also based on the registered number of injuries.

<table>
<thead>
<tr>
<th>Category</th>
<th>costs in million €</th>
<th>registered number</th>
<th>Costs per registered person in million €</th>
<th>real number</th>
<th>Costs per real person in million €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatalities</td>
<td>1556</td>
<td>1,163</td>
<td>1,338</td>
<td>1,163</td>
<td>1,338</td>
</tr>
<tr>
<td>Hospital</td>
<td>3605</td>
<td>11,717</td>
<td>0,308</td>
<td>20,190</td>
<td>0,179</td>
</tr>
<tr>
<td>First Aid only</td>
<td>92</td>
<td>16,795</td>
<td>0,005</td>
<td>108,000</td>
<td>0,001</td>
</tr>
</tbody>
</table>

Table 4-1: Costs related to accidents on the Dutch highway system in 1997 [32]

This table shows an average cost per injury (hospital and first aid) of € 130 thousand (in prices of 1997). Other studies show estimations of the costs of individual accidents that are of the same magnitude. A summary is given in the table below (Figure 4-1).

<table>
<thead>
<tr>
<th>Category</th>
<th>Value in million €</th>
<th>Comment</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatality cost</td>
<td>1,5</td>
<td>Valuation of accident risk is the VSL</td>
<td>UNITE [45]</td>
</tr>
<tr>
<td>Serious injury cost</td>
<td>0,195</td>
<td>Estimated as 13 % of VSL</td>
<td>RECORDIT [46]</td>
</tr>
</tbody>
</table>

Figure 4-1: Estimating costs of individual accidents (in prices of 2000)

Conclusion
For this study the following monetary values are used to determine the immaterial costs. They are expressed in prices of 2002.

Fatalities: 1,5 million €
An average for injuries: 0,175 million €
4.3.3 Material damage

Material damage was not included in the Tunprim model. It was added in order to get a complete overview of the economic consequences of accidents in tunnels. For this purpose an investigation of the damage costs of tunnel accidents was done.

There are three categories of material damage in the case of tunnel accidents:

- damage costs of vehicles, they depend on the type of vehicle: car, bus or truck and on the type of accident: breakdown, only material damage (UMS) or an injuries accident.
- damage costs of the tunnel caused by collisions to the tunnel lining, but moreover by fires. Especially fires with trucks carrying dangerous goods cause enormous damage and can even threaten the integrity of the tunnel.
- damage costs of the tunnel equipment are caused by fires destroying the equipment, so these costs comprise the costs to remove and re-install ventilation, CCTV, fire detection systems etc.

An investigation of damage costs made for the BOMVIT model\textsuperscript{38}, showed the following damage costs represented in Figure 4-2. The three categories used here are:

- only material damage accidents (UMS)
- injury accidents
- fatality accidents

<table>
<thead>
<tr>
<th>Material damage to the vehicle per accident</th>
<th>UMS</th>
<th>Injury</th>
<th>Fatally</th>
</tr>
</thead>
<tbody>
<tr>
<td>car</td>
<td>€2,000</td>
<td>€5,000</td>
<td>€15,000</td>
</tr>
<tr>
<td>truck</td>
<td>€5,000</td>
<td>€20,000</td>
<td>€150,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material damage to the tunnel</th>
<th>UMS</th>
<th>Injury</th>
<th>Fatally</th>
</tr>
</thead>
<tbody>
<tr>
<td>car</td>
<td>€100</td>
<td>€2,000</td>
<td>€4,000</td>
</tr>
<tr>
<td>truck</td>
<td>€1,000</td>
<td>€5,000</td>
<td>€10,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EV of total damage caused by one singel accident</th>
<th>UMS</th>
<th>Injury</th>
<th>Fatally</th>
</tr>
</thead>
<tbody>
<tr>
<td>(assuming that 25 % of the accidents involve damage to the tunnel)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>car</td>
<td>€2,025</td>
<td>€5,500</td>
<td>€16,000</td>
</tr>
<tr>
<td>truck</td>
<td>€5,250</td>
<td>€21,250</td>
<td>€152,500</td>
</tr>
</tbody>
</table>

Figure 4-2: Damage costs for three types of accidents [33,51] (prices of 2002)

Before using these data in the Tunprim model, there are two aspects that need to be considered. First of all the Tunprim model uses three other categories than the BOMVIT model: breakdown, UMS (only material damage) and injury accidents (including both injuries and fatalities). Another difference between the two models is that the BOMVIT model focuses on the normal accidents, while the Tunprim model is made for the evaluation of splc-accidents. This means that the event tree of the Tunprim model is more sophisticated. For example the BOMVIT model does not distinguish fires, which can influence the amount of damage to a great extend.

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\textsuperscript{38} “Beslissings Onderstund Model Vluchtstrook In Tunnels” [33, 51], a model under development at the department of road design of the Ministry of Transport. The model investigates the relation between investments in the construction of a shoulder in relation the decrease in risk. The faulttree of the model is given in appendix D.2, a shematisation of the model is presented in paragraph 6.2.1
Since it is impossible to estimate the risk for every single scenario, several damage categories were defined. These categories correspond with the most important events in the event tree of the Tunprim model:

- type of accident: breakdown, only material damage (UMS) or injury accident
- type of vehicle: car, bus or truck
- type of truck load: non flammable, slightly flammable or dangerous
- presence of dangerous goods: Liquid Toxic, Liquid Gas, Flammable Toxic or Flammable Gas
- presence of a leak: not relevant; 0,5 m$^3$; 5 m$^3$ or instant
- presence of a fire: yes or no

4.4 Description of the categories used to calculate material damage costs

The damage categories defined for the material damage estimation are presented in Figure 4.3. A description of every category follows below. A complete overview of the scenarios in Tunprim and their damage category is given in Appendix D.4. The same scenarios are also represented in the form of an event tree in appendix D.3.

**Category N:** Breakdown accidents of cars, trucks and busses. It is assumed that breakdown accidents will not cause any damage to the tunnel. The costs of a breakdown accident only exist of costs related to towing away the vehicle. For this service, the Ministry of Transport usually has a contract with a garage in the neighbourhood. The contract payments divided by the expected number of breakdown accidents for a standard tunnel gives the costs per accident. (est.)

**Category I:** Only material damage accident with a car. [33]

**Category IB:** * Only material damage accidents with trucks and busses [33]
  * Injury accidents of cars with no fire. [33]

**Category II:**
  * Injury accident with a car resulting in fire\(^{39}\), the car is considered to be total loss (est.)
  * Injury accident with a bus without a fire, the damage is repairable (est.)

**Category IIB:** Injury accidents involving trucks loaded with non-flammable and slightly flammable goods but without a fire. The trucks are considered to be total loss. (est.)

**Category III:**
  * Injury accidents with trucks loaded with dangerous goods (all), but without a fire. The trucks are total loss and are more valuable than normal trucks (est.)
  * Injury accidents with trucks loaded with Liquid Flammable goods and a little leak of 0,5 or 5 m$^3$, but without a fire. (est.)
  * Injury accidents with a truck (normal load) and resulting in fire. The truck is total loss, the cargo is lost and there is damage to the tunnel (est.).

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>50</td>
</tr>
<tr>
<td>I</td>
<td>2,000</td>
</tr>
<tr>
<td>IB</td>
<td>6,000</td>
</tr>
<tr>
<td>II</td>
<td>10,000</td>
</tr>
<tr>
<td>IIIB</td>
<td>50,000</td>
</tr>
<tr>
<td>III</td>
<td>100,000</td>
</tr>
<tr>
<td>IIIIB</td>
<td>500,000</td>
</tr>
<tr>
<td>IV</td>
<td>1,000,000</td>
</tr>
<tr>
<td>IVB</td>
<td>5,000,000</td>
</tr>
<tr>
<td>V</td>
<td>10,000,000</td>
</tr>
<tr>
<td>VB</td>
<td>50,000,000</td>
</tr>
<tr>
<td>VI</td>
<td>100,000,000</td>
</tr>
<tr>
<td>VIIB</td>
<td>500,000,000</td>
</tr>
</tbody>
</table>

Figure 4-3: Damage categories defined for the estimation of material damage

\(^{39}\) Breakdown accidents that result in a fire, are put in the same category as the “injury accident with a fire”
Category IIIB: Injury accidents with trucks loaded with Liquid Flammable goods leaking instantly, but without a fire. The high costs comprise the truck, safety measures that need to be taken to prevent escalation of the incident and cleaning of the tunnel after the accident (est.).

Category IV: * Injury accident with busses and with a fire, the bus is considered total loss, but most of all the fire will cause a lot of damage to the tunnel (est.)
* Injury accidents with trucks loaded with toxic liquid or gas and a fire (the cargo is lost). (est.)
* Injury accidents with a truck with slightly flammable goods and a fire (the cargo is lost). This fire can cause considerable damage to the tunnel. (est.)

Category IVB: * Injury accident with a truck loaded with flammable liquid or gas with a small leak of 0,5 or 5 m³ and a fire. There is much damage to the tunnel and its equipment, because the fire spreads easily. (est.)
* Injury accident with a truck loaded with flammable gas with a continuous leak, but no danger for explosion. (est.)

Category V: * Injury accident with a truck loaded with flammable liquid, an instant leak and a fire. The flammable liquid will spread and cause damage to the tunnel in a large area (est.)

Category VB: -
Category VI: -

Category VIB: All scenarios involving fires of explosive goods (such as flammable gas) that detonate and explode. They pose a threat to the integrity of the tunnel structure, so the damage costs for these scenarios are assumed to be equal to the new investment costs (est.).

4.5 Including the indirect costs of tunnel accidents

On top of the direct costs there are also macro-economic costs. These costs are the indirect costs and comprise costs related to:
- delay of traffic because of traffic jams resulting from accidents
- delay of traffic due to lowered speed limits
- delay of traffic during reconstruction of the tunnel after the accident
- deviation of traffic due to the collapse of a tunnel
- decreasing traffic volume (rerouting) caused by negative emotions due to recent tunnel injuries
- environmental damage

The Dutch Ministry of Transportation uses the costs of delay to investigate the need for new roads. When a large reduction of travel time is expected, a new highway is considered. In a macro-economic evaluation, investments in a new road must meet the monetary gain in loss of travel time. Thus it is logic to investigate the costs of delay caused by accidents in tunnels.
The other costs related to re-routing and environmental damage are hard to assess, so for this project only the costs caused by traffic delay are taken into account. Costs of traffic delay are calculated by multiplying the loss of time with the appreciation of time:

$$\text{Delay costs} = \text{loss of time (hours)} \times \text{average valuation of time (€/hour)}$$

It is clear that the delay costs vary for different users of a highway. The table below (Table 4-2) gives the valuation of time according to the motive of the various users and their share in the total traffic volume:

<table>
<thead>
<tr>
<th>Type of user</th>
<th>time valuation (€/h) [33]</th>
<th>composition of traffic [20]</th>
</tr>
</thead>
<tbody>
<tr>
<td>commuting traffic</td>
<td>6,5</td>
<td>50%</td>
</tr>
<tr>
<td>business traffic</td>
<td>23,0</td>
<td>25%</td>
</tr>
<tr>
<td>other traffic</td>
<td>4,5</td>
<td>10%</td>
</tr>
<tr>
<td>trucks</td>
<td>35,0</td>
<td>15%</td>
</tr>
</tbody>
</table>

Table 4-2: Example of time valuation for different users of the highway system used for the Bored tunnel case.

The average valuation for the loss of an hour for this example yields 14,7 €/h. The delay costs of accidents are calculated with the BOMVIT\textsuperscript{40} model, a model under development at the department of road design of the Ministry of Transport. The model compares the relation between investments in shoulders (resulting in less accidents) and the reduction in time delay.

In this research delay costs resulting from accidents and due to separating dangerous goods are taken into account. The delay for the transport of dangerous goods as a result of convoying this type of transport is estimated to be on average half an hour per truck. The delay resulting from speed limits in the three tunnels is not taken into account because they are negligible\textsuperscript{41}.

### 4.6 Present Values of the risk of the three cases

Like the investment costs in tunnel safety, the risk for the three cases is also expressed in a Present Value. This makes it possible to compare the costs of safety measures with their reduction in risk. For the three tunnels as they are built, the PV of the different damage categories is given in table below (Table 4-3)

<table>
<thead>
<tr>
<th>Case</th>
<th>Total PV</th>
<th>PV fatalities</th>
<th>PV injuries</th>
<th>PV material risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bored tunnel</td>
<td>39,2</td>
<td>16,1</td>
<td>20,9</td>
<td>2,2</td>
</tr>
<tr>
<td>Land tunnel</td>
<td>78,0</td>
<td>30,3</td>
<td>38,3</td>
<td>9,4</td>
</tr>
<tr>
<td>Immersed tunnel</td>
<td>73,8</td>
<td>21,3</td>
<td>39,5</td>
<td>13,0</td>
</tr>
</tbody>
</table>

Table 4-3: Overview of the Present Values (for 30 years) of the risk for the three cases investigated as they are built in million € (base year 2002).

\textsuperscript{40} “Beslissings Onderstuuend Model Vluchtstroken In Tunnels [33, 51]”

\textsuperscript{41} The expected delay per car as a result of a speed reduction of 20 km/hour for the Bored, Land and Immersed tunnel are respectively 100s, 12 and 6 s. The relatively large delay for the Bored tunnel is small in relation to the gain in time as a result of the construction of the tunnel as compared to the situation with the ferries.
5 Investigating the cost effectiveness of safety measures for three tunnel cases

Now that both the costs of safety measures and the risk can be estimated, it is possible to investigate the cost effectiveness of safety measures for several tunnels. Three cases were selected for this purpose. Their main characteristics are described in paragraph 5.1. A summary of the assumptions made for the evaluation of safety measures is given in paragraph 5.2. Then the cost effectiveness in relation to the direct risk is described in paragraph 5.3. Finally the cost effectiveness of the selected safety measures are discussed in paragraph 5.4 including the indirect costs of traffic delay following an accident.

5.1 Description of the three cases investigated

The cost effectiveness of safety measures is investigated using three tunnels in the Netherlands. They have in common that they are all highway tunnels and were in the design or construction phase during this research. So a lot of information was available about the costs of the various safety measures applied and considered in these tunnels. Moreover safety analysis had been done for two of them. In order to see the differences in cost effectiveness for different types of tunnel constructions, an immersed tunnel was compared with a bored tunnel and a land tunnel. Figure 5-1 gives an overview of the characteristics of the three cases used for the evaluation of safety measures.

![Table showing characteristics of three tunnel cases]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Bored Tunnel</th>
<th>Land Tunnel</th>
<th>Immersed Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>length (m)</td>
<td>6600</td>
<td>2000</td>
<td>1100</td>
</tr>
<tr>
<td>expected traffic intensity in 2020</td>
<td>19200</td>
<td>48500</td>
<td>63000</td>
</tr>
<tr>
<td>(veh/day, two ways)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of lanes</td>
<td>2*2</td>
<td>2*2</td>
<td>1<em>2 + 1</em>2 off/ramp</td>
</tr>
<tr>
<td>shoulder</td>
<td>no</td>
<td>yes</td>
<td>yes / no</td>
</tr>
<tr>
<td>Permission to transport dangerous</td>
<td>Cat I</td>
<td>Cat 0</td>
<td>Cat I</td>
</tr>
<tr>
<td>goods</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-1: Characteristics of the three tunnel cases

5.2 Summary of boundaries conditions and assumptions

Below a summary is given of the boundaries and assumptions that are made for this study:

- the probabilistic approach is most suitable because it allows the examination of the cost effectiveness of safety measures.
- Safety is expressed in terms of an Expected Value (risk neutral) and a Characteristic Value (risk averse).
- The focus of this research is on internal safety in tunnels.
- All tunnels must meet the Group Risk criterion (derived from the external safety criterion), before an economic optimisation on safety measures can take place.
- The traffic volumes used for calculating the Group Risk are the maximum daily traffic volumes as expected values for the year 2032.

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42 TNO did a research on the internal and external safety level of the Land tunnel and the Ministry of Transport evaluated the safety level of the Bored tunnel.
43 Classification of the tunnel according to the transport of dangerous goods that is permitted
Category 0: no restrictions; Category I: Exclusion of toxic goods and explosives, no restriction on LPG and tankers; Category II: Exclusion of LPG and tankers, no restriction on diesel trucks
For the economic analysis, an average traffic volume (during the economic lifespan of 30 years) is taken at 80% of the maximum throughput.

5.3 Direct risk: cost effectiveness of safety measures

As mentioned before in this investigation, cost optimisation is only be investigated when the design of a tunnel meets the Group Risk criterion represented in the form of a F-N curve. If this is the case, cost optimising can be done either by removing safety equipment that is not cost effective or by adding cost effective measures. The cost effectiveness can be represented in a figure showing the costs of safety measures versus the risk. Figure 5-2 is an example of such a figure. The vertical axis shows the investments in safety. Above the level 0 are the extra investments for additional safety measures, below the savings on investments of removing safety equipment. The horizontal axis shows the calculated risk for various options of removing or adding equipment. The risk comprises all direct costs: fatalities, injuries and material damage. Note that the safety level is thereby expressed solely in money and increases with a decreasing amount of money. On the right hand side, the risk level 0 represents absolute safety.

![Figure 5-2: Investments in tunnel safety equipment versus risk](image)

Figure 5-3 gives an example for an imaginary tunnel. The grey dot in the middle corresponds with the tunnel as built (reference point) with a risk amount of €200 million over 30 years. All alternatives of adding or removing equipment can then be plotted in the same figure. The two square blocks show areas where no safety measures are to be expected; more investments will not result in more risk and fewer investments will not result in less risk. The line through the reference point “as built” shows a one-on-one relation between investment costs and risk. So safety measures plotted in the two green triangles are considered to be cost effective, because their costs/savings are lower than the reduction/increase in risk. The safety measures in the red triangles are not cost effective, while their costs/savings are higher than their reduction/increase in risk.
These figures were produced for the three cases, both for the Expected Values and the Characteristic Values of risk. The numbers in the figures correspond with the following alternatives:

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>as built (reference point)</td>
</tr>
<tr>
<td>2</td>
<td>without any equipment</td>
</tr>
<tr>
<td>3</td>
<td>construction or removal of a shoulder</td>
</tr>
<tr>
<td>4</td>
<td>halving the number of cross connections</td>
</tr>
<tr>
<td>5</td>
<td>doubling the number of cross connections</td>
</tr>
<tr>
<td>6</td>
<td>removing the heat resistant lining</td>
</tr>
<tr>
<td>7</td>
<td>removing fire equipment</td>
</tr>
<tr>
<td>8</td>
<td>removing the ventilation equipment</td>
</tr>
<tr>
<td>9</td>
<td>sprinkler installation</td>
</tr>
<tr>
<td>10</td>
<td>Speed Detection System (extension beyond the tunnel exits)</td>
</tr>
<tr>
<td>11</td>
<td>separating the transport of dangerous goods</td>
</tr>
<tr>
<td>12</td>
<td>decreasing speed limit with 20 km/h</td>
</tr>
<tr>
<td>13</td>
<td>improving the use of the extinguish tools</td>
</tr>
<tr>
<td>14</td>
<td>improving the use of the escape routes</td>
</tr>
<tr>
<td>15</td>
<td>introduction of a minimum distance between vehicles</td>
</tr>
</tbody>
</table>

Table 5-1: Overview of the safety measures investigated for the three cases.

For the effects of the various safety measures mentioned in the table above a reference is made to paragraph 3.4. For the alternative referred to as *without any equipment* the following assumptions were made:

- the reaction time of the tunnel operator was set at 30 minutes because there are no detection systems.
- Installations like ventilation, PA system, CO-detection and heat detection were removed together with the heat resistant lining
- cross connections were removed
- The percentage of fires that are extinguished is set at 0%, because there are no fire extinguish facilities.
The main results are presented in the following paragraphs, all other figures regarding the cost effectiveness of safety measures for the three tunnels are presented in appendix E.5.

5.3.1 Direct risk for the Bored tunnel case
The cost effectiveness of safety measures for the Bored tunnel can be represented with the following figures. Figure 2-1 shows the costs of safety measures in relation to the Expected Value of total risk.

![Figure 2-1: Costs of safety measures in relation to the Expected Value of total risk in million Euros](image)

**Figure 5-4: Costs of safety measures for the Bored tunnel case in relation to the direct risk (Expected Value) in million Euros**

Removing safety equipment
First of all let’s discuss the removal of safety measures. Figure 5-4 shows that removing safety measures 6 and 8 (removing the heat resistant lining and ventilation) is not cost effective since the increase in risk is higher than the savings on the safety equipment. Enlarging the distance between the cross connections from 250 m to 500 m (nr. 4) and removing the fire equipment (7) however, both save money and do not have much influence on the level of safety and therefore can be done from an economic point of view. An Fn-curve for the Bored tunnel without fire extinguishers is presented in appendix E.3. It shows that even without fire extinguishers the tunnel still meets the Group Risk criterion.

Additional measures
It is clear from Figure 5-4 that for the Bored tunnel case the following additional safety measures are not cost effective in relation to the EV (a risk neutral approach):

- (5) decreasing the distance between the cross connections from 250 m to 100 m. The related costs are high and the effect on the safety level is low.
- (9) installing a sprinkler system. In spite of the large investment (€ 50 million), there is very little influence on the total risk.

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44 The alternative “without any equipment” is left out of the figures, because otherwise the scale of the figures would be too large. These complete figures are given in appendix E.3. For the Bored tunnel the construction of a shoulder is not included for the same reason in figure 5.4.

45 For the escort of dangerous goods, the delay costs are taken into account, the rest of the damage costs in this figure are direct costs.
(11) separating the transport of dangerous goods. Although there is a positive effect on the level of safety, the costs of delay involved with convoying this type of transport are higher than the gain in safety.

Reducing the speed limit (12) and enforcing the minimum distance between all vehicles (15) are both very cost effective safety measures. The investment costs are very low and their effect is high, because they reduce the probability of occurrence of all scenarios.

Other measures like improving the use of escape routes & fire extinguish facilities and extending the SDS beyond the exit of the tunnel are neutral because they do not cost much, but don’t have a large influence either.

**Characteristic Value**

If we take into consideration the social aversion of large scale accidents and therefore use the risk averse Characteristic Value (see paragraph 2.3.3), to evaluate cost efficiency, we get the next picture Figure 5-5.

![Figure 5-5: Costs of safety measures versus risk (CV) in million €](image)

**Figure 5-5:** Costs of safety measures for the Bored tunnel case in relation to the direct risk (Characteristic Value) in million Euros

The differences in the cost efficiency relations for the various safety measures for the Bored tunnel case in relation to the Characteristic Value instead of the Expected Value are very small. In relation to the CV, separating the transport of dangerous goods nearly becomes cost effective.

Another representation of the correlation between the costs of safety and risk is given in Figure 5-6 below. The reference point again is the tunnel as built. Left of this alternative are the options of removing equipment, while the additional measures are given on the right hand side. This figure also includes the alternatives: construction of a shoulder (3) and the tunnel without equipment (2). It clearly shows that both options are not cost effective.
5.3.2 Direct risk for the Land tunnel case
The same figures are presented for the Land tunnel case. First of all the investments costs in tunnel safety versus the Expected Value of risk is given in the figure below (Figure 5-7).

46 The alternatives without any equipment (2) and without the heat resistant lining (6) are not in this figure, because otherwise the scale would become too large. A figure including these measures is given in appendix E.3.
47 The influence of a shoulder on the indirect damage costs is investigated in paragraph 5.4.
Adding safety measures

Regarding the additional safety measures, separating dangerous cargo from the rest of the traffic (11) and installing a sprinkler installation (9) are not feasible. Changing the distance between the escape doors (5) doesn’t cost much for this land tunnel, but does not have a large influence either. The other additional safety measures are cost effective. First of all improving the use of extinguishing tools (13) and escape routes (14). More cost effective is defining a minimum distance between all vehicles (15) and extending the SDS beyond the tunnel exit (10). But the most cost effective safety measure is a speed reduction in the tunnel (12).

Characteristic Value

The cost efficiency of the safety measures in relation to the CV of the risk for the Land tunnel case is presented in Figure 5-8 below.

![Figure 5-8: Costs of safety measures for the Land tunnel case in relation to the direct risk (Characteristic Value) in million Euros](image)

Removing safety equipment

Strangely this figure shows safety measures that installing a sprinkler (9) will have a negative effect on the risk level. This is caused by the formula used to calculate the Characteristic Value:

\[ CV = EV + k \times \sigma (N) \]

with:

\[ \sigma_N^2 = \sum \text{(probability} \times (N - EV)^2 \text{)} \]

where:

- \( CV \): Characteristic Value
- \( EV \): Expected number of fatalities (N)
- \( \sigma (N) \): Standard deviation of the number of fatalities (N)
- \( k \): Number defining the probability of exceeding, for evaluation risks in tunnels, \( k \) is usually taken as 3\(^4\)

Figure 5-9 shows two probability density functions (pdf); for a reference situation and a new one. The new distribution has a lower EV (increasing

\(^4\) For a standard-normal probability density function and \( k = 3 \) the probability of exceeding is 0.1 % per year [50].
safety), but since the “s plc accidents” may still occur, it is stretched out and therefore the standard deviation increases. So even if the Expected Value of the risk decreases as a result of a safety measure, when the standard deviation \( \sigma (N) \) increases even a little bit, it is possible that the CV increases. This is due to the lack of mathematical background of this parameter.

Figure 5-9: The standard deviation of a pdf can increase when the EV of large-scale accidents drops.

This explains why the CV for the sprinkler installation increases even though we can expect that the safety level will increase after installation of a sprinkler system.

It is clear that installation of a sprinkler system is not a cost effective measure, while the high installation costs do not result in a large reduction of the risk. All options regarding the removal of safety equipment are not cost effective in relation to the CV.

Adding safety measures
Figure 5-8 shows that all additional safety measures are cost effective in a risk adverse approach for the Land tunnel case.

5.3.3 Direct risk for the Immersed tunnel case
Below the cost efficiency of the safety measures for the Immersed tunnel case is presented (Figure 5-10).

Figure 5-10: Costs of safety measures for the Immersed tunnel case in relation to the direct risk (Expected Value) in million Euros
Removing safety measures
Like in the Land tunnel case, removing the shoulder in the Immersed tunnel is a cost effective measure in relation to the Expected Value of direct risk. The savings on removing the ventilation equipment and the fire extinguish facilities are of the same magnitude as the increase of direct risk\textsuperscript{49}. Removing the heat resistant lining is not cost effective\textsuperscript{50}.

Characteristic Value
For the Characteristic Value of the direct risk, the relation between investments and risk is presented in Figure 5-11. It is clear that again the sprinkler installation is not cost effective and that the removal of the shoulder is not cost effective concerning the CV. Of all the other safety measures where removal was investigated, it turned out to be not cost effective. All additional safety measures are cost effective.

\textbf{Figure 5-11: Costs of safety measures for the Immersed tunnel case in relation to the direct risk (Characteristic Value) in million Euros}

5.4 Indirect risk: cost effectiveness of safety measures
Since the analysis of cost effectiveness in relation to the direct risk showed that removing the shoulders from the Immersed tunnel and Land tunnel is cost efficient with respect to the EV, an investigation was done on the indirect costs. The indirect costs are the costs as a result of traffic delays following an accident in a tunnel. An analysis was done on this safety measure using the BOMVIT model\textsuperscript{51}. The event tree of the BOMVIT model is included in appendix D.2.

5.4.1 Including the indirect risk for the Bored tunnel
The traffic intensities in the Bored tunnel are very low. One traffic lane in each direction is more than sufficient even during rush hour. So indirect risk from delays are only expected when the whole tunnel has to be closed after a huge

\textsuperscript{49} Again removing the ventilation system and the fire extinguish facilities is possible regarding the Group Risk criterion.

\textsuperscript{50} Again this safety measure is not in the figure, because it would change the scale and make it hard to distinguish the other safety measures. The whole figure is given in appendix E.3.

\textsuperscript{51} "Beslissings Ondersteunend Model voor Vluchtstroken in Tunnels", a probabilistic model under construction at the Ministry of Transport, division road design in Apeldoorn. The model evaluates the indirect costs of delays due to traffic jams following an accident in relation to the investment costs of shoulders that can decrease the accident frequency.
accident. These accidents however occur with such a low probability that the extra costs of constructing a shoulder are not justified (for the Bored tunnel case estimated to be 283 million Euro). In appendix E.6 the output of the model for the Bored tunnel is given.

5.4.2 Including the indirect risk for the Land tunnel

For the Land tunnel the alternative with a shoulder (reference situation) was compared with a design without a shoulder and a tunnel with a shoulder that is turned into a traffic lane half way its economic lifespan. A summary of the results of an analysis including direct and indirect risk is presented in Figure 5-12. It shows that both these options will reduce the total Present Value of the project. It is clear from this analysis that the risk mainly consists of costs related to congestion.

Turning the shoulder into a traffic lane after 15 years (third column) will result in less congestion due to accidents and therefore reduces the PV of the project (with € 3,2 million\(^{52}\)). Even more profitable is removing the shoulder in the Land tunnel. It will reduce the total investment with € 15,4 million (PV). Though the risk will increase with € 7,2 million (PV). This means that still the total Present Value of a tunnel without a shoulder is about € 8,1 million lower than the one with a shoulder. Thus it can be concluded that a shoulder is not a cost effective safety measure, even if the indirect risk resulting from traffic delay are taken into account.

\(^{52}\) All these Present Values are calculated using total cost including taxes and are expressed in Euros with the base year 2002.
Table 5-12: Present Values of total direct AND indirect risk for the Land tunnel case, with a shoulder (reference), without a shoulder and with a shoulder that is turned into a traffic lane after 15 years.

### 5.4.3 Including the indirect risk for the Immersed tunnel

The configuration of the Immersed tunnel is somewhat different from the other two, because the two tubes are not alike. One of them has two lanes and an on/off ramp, while in the other direction there are two traffic lanes and a shoulder. The following alternatives were considered:

- **3 lanes WITHOUT shoulder (reference situation)**
- **3 lanes WITHOUT shoulder (removing 1 shoulder)**
- **3 lanes WITH shoulder (adding 1 shoulder)**
- **2 lanes WITH shoulder.**
- **2 lanes WITHOUT shoulder**

---

53 Casualties resulting from calamities are neglected in this model, because their expected value is considered to be too low.
Figure 5-13 shows a summary of the total risk for the 3 options. It is clear that here too, removing the shoulder is a cost effective measures, even when the indirect risk are included. However, one must take into consideration that the traffic volumes estimated for the Immersed tunnel show serious congestion for the alternatives with 2 lanes in the near future (2020).

<table>
<thead>
<tr>
<th>Case: Immersed tunnel</th>
<th>Reference</th>
<th>removing 1 shoulder</th>
<th>adding 1 shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Casualties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>accidents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>injured</td>
<td>€ 3.172.000</td>
<td>€ 3.683.000</td>
<td>€ 3.172.000</td>
</tr>
<tr>
<td>fatalities</td>
<td>€ 4.250.000</td>
<td>€ 4.936.000</td>
<td>€ 4.250.000</td>
</tr>
<tr>
<td>Calamities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>injured</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>fatalities</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Material damage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>accidents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>material damage to the vehicles</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>material damage to the tunnel</td>
<td>€ 2.220.000</td>
<td>€ 2.448.000</td>
<td>€ 2.220.000</td>
</tr>
<tr>
<td>Calamities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>material damage to the vehicles</td>
<td>€ 106.500</td>
<td>€ 118.600</td>
<td>€ 106.500</td>
</tr>
<tr>
<td>material damage to the tunnel</td>
<td>€ 10.410</td>
<td>€ 10.410</td>
<td>€ 9.540</td>
</tr>
<tr>
<td><strong>Congestion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>breakdown accidents</td>
<td>€ 82.000</td>
<td>€ 4.659.000</td>
<td>€ 61.000</td>
</tr>
<tr>
<td>accidents</td>
<td>€ 5.973.000</td>
<td>€ 10.823.000</td>
<td>€ 1.123.000</td>
</tr>
<tr>
<td>calamities</td>
<td>€ 149.000</td>
<td>€ 149.000</td>
<td>€ 124.200</td>
</tr>
<tr>
<td>maintenance</td>
<td>€ 0</td>
<td>€ 0</td>
<td>€ 0</td>
</tr>
<tr>
<td><strong>Total without investments</strong></td>
<td>€ 16.058.000</td>
<td>€ 29.922.000</td>
<td>€ 11.153.000</td>
</tr>
<tr>
<td>difference</td>
<td>€ 0</td>
<td>€13.864.000</td>
<td>€ 4.905.000</td>
</tr>
<tr>
<td><strong>Maintenance (30 years)</strong></td>
<td>€ 37.524.000</td>
<td>€ 35.622.000</td>
<td>€ 41.155.000</td>
</tr>
<tr>
<td>investments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Net Present Value (30 years)</strong></td>
<td>€ 286.284.000</td>
<td>€ 283.450.000</td>
<td>€ 307.529.000</td>
</tr>
<tr>
<td>difference</td>
<td>€ 0</td>
<td>-€ 2.834.000</td>
<td>€ 21.245.000</td>
</tr>
</tbody>
</table>

Figure 5-13: Present Values of total direct AND indirect risk for the Immersed tunnel case.
6 Evaluation of the results of the cost effectiveness analysis

Now that a relation is presented between the costs of safety measures and the gain in safety, it is time to evaluate the results of the investigation. First of all the shortcomings of the risk assessment method used are described in paragraph 6.1. Then a sensitivity analysis shows the influence of the investment costs and the input data used in the models (6.2). Finally an evaluation is given of the results of this investigation (6.3).

6.1 Risk assessment method

6.1.1 Probabilistic approach
The advantages of the probabilistic approach used for this research are clear. This method makes it possible to examine all possible scenarios in a tunnel. Besides it enables an economic estimation of the risk related to tunnel accidents (costs related to fatalities, injuries and material damage), which is essential for an evaluation of the cost efficiency of safety measures. On the other hand one must realise that the estimation of the parameters used in probabilistic models are based on little data. Tunnel safety can therefore become a tough debate.

6.1.2 Using the Expected Value and Characteristic Value
The two statistical values used in this investigation have their advantages and disadvantages.

Expected Value (EV)
The Expected Value is the sum of the probability times the consequences of all different scenarios (risk neutral). Its main advantage is that it is suitable to calculate the risk to society in order to come to a purely economical judgement on which safety measures have to be applied. A disadvantage is that it does not distinguish between scenarios with a high probability times a low consequence or a low probability times a high consequence. The Expected Value of large-scale accidents with a very low probability is almost negligible. For example the probability of losing a tunnel due to an explosion is estimated to be about 2 times per million years for the Immersed tunnel case, with a damage of amount of about € 200 million and thus the EV per year is € 400,-. This means that these splc-accidents have only very limited influence on the EV. Fighting scenarios concerning splc-accidents can therefore never be cost effective regarding the EV.

Characteristic Value (CV)
The CV was used to take into account the social aversion of large-scale accidents by adding the standard deviation to the EV (as described in paragraph 2.3.3).

\[ CV = EV + k \cdot \sigma (N) \]

with:

\[ \sigma_{\text{N}}^2 = \sum (\text{probability} \cdot (N - EV)^2) \]

where:

\[ 2 \cdot 10^{-6} \cdot 200 \cdot 10^{6} = € 400,- \]
The value of $k$ determines the weight one wants to assign to these large-scale accidents. The value 3 used here is often used for risk assessment in tunnels. The figures presented in chapter 5 clearly show that some safety measures can be considered cost effective in relation to the CV, while they are not cost effective in relation to the EV. The removal of a shoulder is cost effective in a risk neutral approach, but regarding the CV (risk averse) it is not cost effective. Separating the transport of dangerous goods through tunnels is also not cost effective in relation to the EV, but is almost cost effective regarding the CV. The Characteristic Value however does not improve the performance of other safety measures that aim specifically at reducing the risks of splc-accidents (installing a sprinkler system or changing the mutual distance of the cross connections).

Moreover, some figures representing the CV show that the risk level increases while an additional safety measure is applied (see paragraph 5.3.2). Of course this does not correspond with reality. It is due to the fact that this statistical value lacks a thorough mathematical background. One must therefore be careful with using this value. More research is needed on a value that takes into account these large-scale accidents in a mathematical correct way.

6.2 Sensitivity analysis

6.2.1 Schematisations made in the models

The Tunprim model used to evaluate the direct risk
The aim of the Tunprim model is to evaluate the risks of splc-accidents. The number of injuries and fatalities is calculated using the following parameters:

- traffic volume; the model is used to compare the safety level of a tunnel with the Group Risk criterion, therefore it uses one traffic volume (the maximum).
- accident frequency; the accident frequencies are different for the slopes and the straight part of the tunnel.
- number of people present in the tunnel; it depends on the time of the day the accident occurs and the place in the tunnel. It is assumed that there is always a traffic jam behind an accident involving a fire and that no vehicle passes the accident. The model uses three places where accidents occur; halfway of the downhill slope, halfway the straight part and halfway the uphill slope. These two assumptions are quite conservative.
- area of influence of all scenarios; the consequences of all accidents are expressed in an area of influence. Within this area (dependable on the scenario), a fixed percentage of people are assumed to die or get injured. A problem with using these areas of influence is that there is very little knowledge about the exact development of splc-accidents and their effects on people present. The parameters used to calculate the area of influence and the number of casualties are therefore educated guesses. The assumptions used in this model are again quite conservative. More research on the area of influence of tunnel accidents involving dangerous goods is needed.
The BOMVIT model used to evaluate direct and indirect risk

The focus of this model is on the expected traffic delay resulting from accidents. Therefore the model is based on three main parameters:

- the traffic throughput
- the accident frequencies
- the traffic delay resulting from an accident

The traffic volume is calculated by estimating the average throughput for two phases of the economical lifespan. Since the growth of the traffic volume is not linear, but exponential, the total traffic throughput is slightly underestimated. This is presented in Figure 6-1 below, with the two grey squares.

![Figure 6-1: Calculation method used in the BOMVIT model to estimate the traffic throughput in a tunnel during its economical lifespan.](image)

The accident frequencies used in the model are assumed to be constant over the total length of the tunnel. However, there are small differences in frequencies depending on the place of a tunnel. One can expect that a driver that needs to pull over as a result of a breakdown will try to stop at the horizontal part of the tunnel and not at the up- and downhill parts. Though the average will be the same. For accidents this is not the case. As reported in paragraph 1.1.2, the accident frequency is higher on the slopes than on the straight part of the tunnel. For relatively small tunnels, these differences are negligible. However for long tunnels, this will result in fewer accidents.

The delay of traffic depends not only the number of accidents, but also on the time it takes to return to the normal situation. The estimation of this parameter therefore has a great impact on the total costs of delay.

6.2.2 Input used in the models

A sensitivity analysis was done to find out the influence of the various input parameters used in the models. This analysis was done with a program called Cristal Ball®. This add-on program to MS Excell can be used to do a Monte-Carlo analysis. In a Monte Carlo analysis, a probability density functions (pdf) can be assigned to all input parameters. The model then draws a value out of these pdf's for every input parameter and starts calculating. After numerous calculations, the output of the model can be represented in the form of a probability density function. The sensitivity of the results in relation to the input

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55 [www.decisioeering.com](http://www.decisioeering.com)
data is calculated by the contribution of each input parameter to the standard deviation of the output parameter. Figure 6-2 gives a graphical explanation.

![Figure 6-2: Relative influence of the input parameters on the standard deviation of the output parameter in a sensitivity analysis done with a Monte Carlo simulation](image)

The results of this sensitivity analysis for the immersed tunnel case are given in Table 6-1 below. The results for the other two tunnels are presented in appendix F.1. The table shows the input parameters that contribute more than 2 % to the deviation of various output parameters. A division is made into the three different types of accidents used in this investigation: normal accidents; jammed accidents and splc-accidents. Added to this are the output parameters of the risk. The sensitivity of the input data is investigated in relation to both the EV and its deviation. It is clear from table 6-1 that the deviation depends on the same parameters as the EV for the three accident types. For the risk however, there are little differences in the influence of the input parameters in relation to the EV and its deviation. Another striking point is that there are mostly 2 or 3 parameters that dominate the output parameter in the three cases.

**Normal accidents**
The number of fatalities and injuries as a result of normal accidents and the standard deviation of the Expected Value depend mainly on the following parameters:
- the traffic intensity
- the modal split of the traffic; percentage of cars versus trucks (trucks have a higher accident frequency).
- number of people wounded or dying per accident
- fire frequency of the cars
- percentage of breakdown accidents that result in fires

**Jammed accidents**
The casualties due to a jammed accident mainly depend on:
- percentage of breakdown accidents that result in fires
- traffic intensity
- fire frequency
- number of people jammed in a car
- injury/fatality rate of the jammed people

**Small Probabilities Large Consequences accidents**
The most influential parameters for the splc-accidents are:
- fire frequency
The risk of tunnel accidents and the standard deviation mainly depend on the following parameters:

- traffic intensity
- modal split of the traffic
- number of trucks loaded with Flammable Gas (land tunnel)
- distance between the escape doors

### Risk

Normal accidents

<table>
<thead>
<tr>
<th>Normal accidents</th>
<th>( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV fatalities and its deviation</td>
<td></td>
</tr>
<tr>
<td>traffic intensity</td>
<td>41%</td>
</tr>
<tr>
<td>percentage of cars of total traffic</td>
<td>22%</td>
</tr>
<tr>
<td>number of fatalities in a truck accident</td>
<td>18%</td>
</tr>
<tr>
<td>accident frequency during rush hour for the ascending part</td>
<td>5%</td>
</tr>
<tr>
<td>accident frequency during day timer for the ascending part</td>
<td>5%</td>
</tr>
<tr>
<td>accident frequency during day timer for the descending part</td>
<td>1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normal accidents</th>
<th>( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV injuries and its deviation</td>
<td></td>
</tr>
<tr>
<td>traffic intensity</td>
<td>55%</td>
</tr>
<tr>
<td>number of people wounded in a truck accident</td>
<td>16%</td>
</tr>
<tr>
<td>number of people wounded in a truck accident</td>
<td>7%</td>
</tr>
<tr>
<td>accident frequency during day timer for the ascending part</td>
<td>4%</td>
</tr>
<tr>
<td>accident frequency during rush hour for the ascending part</td>
<td>4%</td>
</tr>
<tr>
<td>accident frequency during day timer for the descending part</td>
<td>3%</td>
</tr>
</tbody>
</table>

Evacuated accidents

<table>
<thead>
<tr>
<th>Evacuated accidents</th>
<th>( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV fatalities and injuries and their deviation</td>
<td></td>
</tr>
<tr>
<td>chance of fire resulting from a breakdown accident</td>
<td>85%</td>
</tr>
<tr>
<td>fire frequency</td>
<td>1%</td>
</tr>
</tbody>
</table>

SPLC-accidents

<table>
<thead>
<tr>
<th>SPLC-accidents</th>
<th>( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV fatalities and injuries and their deviation</td>
<td></td>
</tr>
<tr>
<td>number of lanes in the tunnel</td>
<td>28%</td>
</tr>
<tr>
<td>chance of the presence of disabled people</td>
<td>11%</td>
</tr>
<tr>
<td>fire frequency</td>
<td>15%</td>
</tr>
<tr>
<td>chance of fire resulting from a breakdown accident</td>
<td>9%</td>
</tr>
<tr>
<td>traffic intensity</td>
<td>8%</td>
</tr>
<tr>
<td>chance of fatal injuries to disabled people within the area of influence breakdown fire with ventilation</td>
<td>7%</td>
</tr>
<tr>
<td>percentage of cars of total traffic</td>
<td>5%</td>
</tr>
<tr>
<td>area of influence during a breakdown of a car with ventilation</td>
<td>3%</td>
</tr>
<tr>
<td>area of influence during a breakdown of a truck with ventilation</td>
<td>3%</td>
</tr>
<tr>
<td>average number of people in a car</td>
<td>3%</td>
</tr>
<tr>
<td>distance between escape doors</td>
<td>1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Risk</th>
<th>( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV risk (€)</td>
<td></td>
</tr>
<tr>
<td>traffic intensity</td>
<td>52%</td>
</tr>
<tr>
<td>percentage of cars of total traffic</td>
<td>26%</td>
</tr>
<tr>
<td>damage category N</td>
<td>5%</td>
</tr>
<tr>
<td>damage category IV</td>
<td>2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Risk</th>
<th>( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>deviation of the risk (€)</td>
<td></td>
</tr>
<tr>
<td>traffic intensity</td>
<td>51%</td>
</tr>
<tr>
<td>percentage of cars of total traffic</td>
<td>23%</td>
</tr>
<tr>
<td>number of trucks loaded with GF</td>
<td>1%</td>
</tr>
<tr>
<td>damage category N</td>
<td>1%</td>
</tr>
<tr>
<td>damage category IV</td>
<td>2%</td>
</tr>
</tbody>
</table>

Table 6-1: Contribution of an input parameter (in terms of percentage) to the deviation of the output parameter, calculated with a Monte Carlo analysis\(^{56}\).

\(^{56}\) In the runs of the Tunpim model the accident frequencies were equal for daytime, rush hour and nighttime. They only vary according to the ascending part, the straight part and the uphill part.
Conclusion

It can be concluded from table 6-1 that the most influential input parameters used in the Tunprim model are the expected traffic volume, the fire frequency of cars, and modal split of the traffic, and the percentage of disabled people present in the tunnel.

- **expected traffic volume**: the number of accidents is the product of the traffic volume and the accident frequency. The model distinguishes various accident frequencies for day time, during rush hour and during night time as well as for the straight part and the two slopes. Thus there are various accident frequencies multiplied with just one traffic volume. If all these accident frequencies were taken as one parameter, the influence would be of the same magnitude as the influence of the traffic volume.
- **fire frequency**: the fire frequency if cars is a property of the cars driving through the tunnel, the Ministry of Transport has little influence on this parameter.
- **modal split of traffic**: the modal split is also a given parameter, it can not be influenced by the Ministry of Transport.
- **percentage of disabled people**: again a given parameter that one can not change.

It can be concluded that most of these parameters are hardly influential by the Ministry of Transport. The only parameter that has a significant influence and that one can be influenced is the accident frequency (for example by construction of a shoulder, introduction of a minimum distance between vehicles or reduce the speed reduction).

If the sensitivity analysis were done without the non-influential parameters mentioned above, the analysis would show the rest of the safety measures on the list, still in the same order. Thus the accident frequencies are the primary parameters of the Tunprim model.

Other parameters that have less effect on the safety level of a tunnel that can be influenced are: the percentage of breakdown accidents that result in a fire, the probability of a traffic jam in the tunnel during rush hour and the distance between emergency exits.

- **percentage of breakdown accidents that result in a fire**: one can reduce the number of breakdown accidents that result in a fire by improving the use of fire extinguish facilities.
- **probability of a traffic jam in the tunnel during rush hour**: extending the Speed Detection System beyond the exit of the tunnel can prevent the built up of a traffic jam in the tunnel during rush hour (see paragraph 3.4.2).
- **distance between emergency exits**: reducing the distance between emergency exits will increase the level of self-help of the people that have to flee an emergency situation. However, these exits are only used to fight the consequences of splc-accidents.

Finally there are parameters regarding the injury/fatality rate of people. They can be tackled with improvements in the performance of medical care and the fire department.

6.2.3 Investment and risk

An evaluation was also done on the influence of the monetary values used to determine the risk and the investment costs.
Risk
The risk of tunnel accidents comprise both material and immaterial damage. Material damage is only important for the alternatives without any equipment, without fire resistant lining and for the sprinkler installation. For all other alternatives the total risk are mainly due to immaterial damage. As can be concluded from the sensitivity analyses done in paragraph 6.2.2, the material risk comprise mainly small accidents (breakdowns and collisions without fires), so the influence of the height of the damage categories used to estimate the material damage is of little influence on the material risk.

The immaterial risk however are the product of the estimated amount of casualties and their monetary values. Therefore it is useful to investigate the influence of these monetary values on the risk. While the material costs calculated for the three cases in Table 4-3, account for 80 % to 95 % of the risk, the total risk is almost linear with the height of the monetary values assigned to casualties. This is important because all safety measures are compared with the tunnel as built (reference point). Therefore if the monetary values for immaterial losses are doubled, the risk of the reference point will also double. All safety measures on the same level of risk will move accordingly. The points of the rest of the safety measures plotted in the cost effectiveness relation will be stretched out. This is pointed out in Figure 6-3 below.

If a cost efficiency analysis is done starting with an empty tunnel, then the monetary values will definitely have more influence on the cost efficiency relation of the safety measures.

Figure 6-3: Influence of the monetary value of immaterial damage on the cost effectiveness relation of safety measures in this investigation

Investment costs
While the investment costs used in this research are based on tunnelling projects at the moment, these costs are estimated values. In reality they can better be represented with probability density functions. Investment costs are usually given in the form of an expected value, a minimum and a maximum.

57 an evaluation for the Bored tunnel case showed that an increase of the monetary values for fatalities and injuries of 25 % resulted in an increase of the total risk with 24 %.
58 except the ones specifically aiming at reducing material damage
value. The minimum value is 10% less than the expected value and the maximum value is 25% more. This can be represented with an Gamma distribution function as given in Figure 6-4.

![Probability density function of a Gamma distribution](image)

**Figure 6-4:** Probability density function of an Gamma distribution as often used for the investment costs

Risk however is represented with a normal distribution. Figure 6-4 shows the combinations of two input parameters with a distribution function and the distribution of the output parameter. While the output parameter is a combination of two 2-dimensional distributions, the output has a 3-dimensional distribution. The black dot in the middle shows the EV of the combination of the two parameters and the lines in the plot show points with an equal probability. The probability drops with the distance from the dot. One can compare it with lines showing the same altitudes used to present mountains on a two-dimensional map.

While the risk in this investigation comprise a lot of input parameters with different distributions, the plot gets even more complicated. Therefore the plots in chapter five regarding the cost efficiency of safety measures do not show the distribution of the output. Since this research is a first step towards cost efficiency safety analysis, it is already useful to see in which area the safety measures under consideration can be expected. For the safety measures that are just about cost efficient, it is interesting to take into account the probability distributions of all the input parameters. Though more research on the probability density function of most of the input parameters is needed.
6.3 Evaluation of the results of the research

The aim of this investigating is to find a correlation between the costs of safety measures and their effect. It is clear from chapter 5 that this correlation was found in relation to the reference point. An evaluation of the results is given in paragraph 6.3.2. Besides an effort was made to find an economical optimum of the safety level. This optimum safety level however could not be found. An explanation is given in paragraph 6.3.1.

6.3.1 Economical optimum safety level

The idea of an economical safety optimum is derived from the economical safety analyses done on the flood defence system in the Netherlands. In this analysis the costs of improving safety (heightening the dykes) are summed with the risk related to flooding. A schematic representation of this optimisation is shown below in Figure 6-6, the straight line represents the investments in heightening the dykes (the higher the dykes, the more investments are needed). The lower curve represents the probability of flooding times the related damage costs (risk). It is clear that when there is no flood defence system, the risk will be considerable. The risk will drop with an increasing height of the dykes. The sum of these two lines results in a “bath tub”-curve. The optimum safety level is found where the total costs are lowest.

Figure 6-5: The probability density function of an output parameter as a product of two input parameters both with a probability density function (Gamma and normal distribution).
Figure 6-6: Schematic representation of the economical safety analysis on the Dutch flood defence system.

While both the investment costs and the risk were calculated for the three tunnel cases, it was tried to present the same type of figure for these three tunnels. Unfortunately this turned out to be impossible for the following reasons:

- **number of safety numbers**: improving the safety level of a flood defence system is schematised in these analysis by investments in just one safety measure that can be applied in a fixed order (heightening the dykes). Improving the safety level in tunnels on the other hand can be done by applying several different safety measures. This has a great impact on the graphic representation of the investment costs. The investments costs for a flood defence system show a clear relation with the height of the dykes and thus the safety level. For a tunnel the relation between the investments in safety and the safety level depends on the order the safety measures are applied. Therefore it is not possible to present one single correlation.

- **effect of a safety measure**: of all the safety measures that are applicable to tunnels, it is not always clear what the effect of the safety measures is on the safety level of the tunnel. More research is needed for a better judgement of the safety measures in tunnels.

- **correlation of the effects of several safety measures**: on one hand it is difficult to assign an effect to a safety measure that works within a complex system, on the other hand it is also hard to determine the influence of a combination of measures (like the traffic management solutions). Therefore it is even harder to present a continuous relation between the costs of safety and the safety level that is achieved. (see 6.3.2.)

A graphic representation of these problems is given in Figure 6-7 below.
Figure 6-7: The relation between investment costs in safety and the level of safety achieved for a tunnel and for a flood defence system.

It is clear that of the 5 measures represented in Figure 6-7, number 1 and 2 have the same level of safety, however the investment costs are different. Safety measures 3 and 4 on the other hand result in a different safety level, for the same amount of investment. Safety measure 5 has the highest safety level and also the highest investment costs.

The cumulative contribution to the safety level of a combination of various safety measures makes the figure even more complicated. However, this figure shows that it is not clear with which safety measure one must start to draw a correlation between investments in tunnel safety and the achieved risk level. In fact there are many. Thus it is not possible to sum the risk with the investment costs to find an optimum.

6.3.2 Correlation between investment costs and the effects of safety measures

As mentioned in the previous paragraph, it is not possible to draw a relation between the costs of improving safety versus the level of safety. Thus for the cost effectiveness analysis, it was not possible to start from an empty tunnel and add equipment to the tunnel till it equals the tunnel as it was built. Instead the tunnel as built was taken as a reference point and all safety measures were evaluated individually. Then these safety measures were plotted in relation to this reference point. This means that the cost efficiency of the safety measures investigated in this research depends on the initial safety level of the tunnel. This is an important fact as one can expect that when no safety measures are present in a tunnel, most of the safety measures under consideration are cost effective, contrary to a tunnel where the safety level of the tunnel is already high. This phenomenon is presented in Figure 6-8 below.
This figure shows again a relation between the investments in safety (vertical) versus the level of safety of a tunnel (horizontal). It is the same relation as used in chapter 5.

Although it is not possible to find a fixed correlation between investment and safety for tunnels (see paragraph 6.3.1), a dotted line in the figure shows a rough estimation of how such a correlation looks like. Following the general economic law of diminishing returns, it can be expected that investments in safety will have much effect in a tunnel without equipment and less effect in a tunnel that is fully equipped. Added to this figure are three black dots representing a tunnel with three different levels of safety equipment. Moreover, the triangles representing the area where safety measures are cost effective (as described in Figure 5-2: Investments in tunnel safety equipment versus risk) are added. It is clear that it is more likely to find cost-effective safety measures for the tunnel on the left (with the lowest level of safety) than for the one on the right (highest level of safety).

The investigation of the three cases was done in relation to the reference point as built, so the level of safety is already high. This may be the reason that most of the installation and structural measures under consideration did not turn out to be cost effective. If the same investigation were done using a tunnel without equipment as reference, maybe some of these measures would have been cost effective. Therefore, it is recommended to do this type of cost effectiveness analysis also for other safety levels than only the tunnel as built.
7 Conclusions and recommendations

This chapter summarises the conclusions and recommendations that follow from this research.

7.1 Conclusions

7.1.1 Risk assessment method used to evaluate the cost effectiveness

Regarding the safety norms applicable to tunnels the following is concluded:

- The probabilistic approach is the best way to evaluate the safety level of a tunnel, because it can be used to define a safety norm and compare the safety levels of several tunnels. Besides, the design scenario in a probabilistic approach follows from the evaluation of all possible scenarios, contrary to the deterministic approach.

- Probabilistic evaluations of risks in tunnels generally only include fatalities. Adding injuries and material risk to the probabilistic model Tunprim is possible. If a monetary value is assigned to the expected number of injuries and fatalities, the direct risk can be expressed solely in money. This enables the evaluation of cost effectiveness of safety measures.

- In a probabilistic economic evaluation of safety measures, it is cost effective to remove certain safety measures from the tunnel as built (remove the fire equipment reduce the number of cross connections). Even then, the tunnel still meets the probabilistic norm for Group Risk. This means that the tunnels as they are designed in the Netherlands at the moment are not designed using solely the objective probabilistic calculation method, but there are also subjective influences.

- Including the indirect costs of traffic delays as a result of tunnel accidents is also possible. It enables a macro-economic evaluation of the cost efficiency of safety measures in tunnels.

- Casualties as a result of normal accidents and people that are stuck (jammed accidents) account for more than 90% of the Expected Value. The EV therefore is not a good way to investigate the “small probability, large consequence accidents”.

- Using the Characteristic Value is a good way to take into account the social aversion of large-scale accidents. A disadvantage of the CV is that it lacks a thorough mathematical background. Therefore it is possible that investments in safety result in an increase of the CV. Of course this does not correspond with reality.

7.1.2 Results of the investigation in general

Regarding the evaluation of the cost efficiency of safety measures for the three tunnels investigated, the following can be concluded in general:

- The probabilistic evaluation of safety showed that the three tunnels investigated in this research all comply with the probabilistic Group Risk criterion represented in the form of an F-N curve.

- It is not possible to find an economic optimum safety level for tunnels using the same approach as is used in economic analysis on flood defence systems for several reasons. First of all, economic optimisation of the flood defence system is usually done with just one safety measure that can be applied at various levels (height of the dyke), while there are several measures that improve the safety level in a tunnel. Another problem is that there is not a lot knowledge about the effects of the a lot of safety measures. Finally, it is hard to determine
the influence of one safety measure. On one hand it is difficult to assign an effect to a safety measure that works within a complex system, on the other hand it is also hard to determine the influence of a combination of measures (like the traffic management solutions). An economic optimum safety level for tunnels therefore can only be found by comparing all sorts of combinations of safety measures (multi variable optimisation).

- A problem encountered when examining combinations of safety measures is that some safety measures have the same effect for different costs, while others have different effects for the same costs.

7.1.3 Conclusions about the cost effectiveness of safety measures
The figures in chapter 5 show a clear relation between the costs of safety measures and the Present Value of risk (Expected Value and Characteristic Value). The following conclusions follow from these cost effectiveness relation regarding the removal of safety equipment and adding safety equipment to the tunnel as built. These figures are not added again to this section, but a reference is made to paragraph 5.3, page 42 to 48.

Removing safety equipment from the tunnels as built:
- Removing the fire resistant lining is a certainly not efficient in all cases and it is therefore not advisable to remove this lining although the costs may be relatively high.
- Removing the ventilation equipment in the three cases is not a cost effective safety measure in relation to the EV and the CV.
- Removing the fire equipment form the tunnels as built seems to be cost effective. Besides, even if the equipment is removed, the tunnels still comply with the Group Risk criterion.

Additional safety measures that can be added to the tunnel as built:
- Extending the Speed Detection System beyond the exits of the tunnel is a very cost effective measure, which eliminates scenarios with a lot of people present in the tunnel during a major fire.
- Separating trucks carrying dangerous cargo from the rest of the traffic is not cost effective in relation to the Expected Value of risk, though it is when the Characteristic Value is taken into account. Besides, it is the most cost effective measure to fight the consequences of “splc-accident”, while it eliminates a lot of these scenarios.
- There are some difficulties in the use of sprinklers. First of all the demands on the detection system are very tough and a little contradicting. It must be failsafe and it must be very sensitive. Besides the effects of a sprinkler installation on the development of a major fire are not completely known. Finally there is a lot of uncertainty on the costs of sprinkler systems in tunnels.
- Sprinkler installations are not cost effective in the three cases, while their costs are considerable and they are only useful in case of splc-accidents. Moreover the schematisation of the sprinkler in this research was quite optimistic, which means that even if the high demands can be met, the sprinkler still is not cost efficient.
- The most cost efficient additional safety measures in tunnels are the regulatory measures like the introduction of a minimum distance between vehicles and improving the use of fire extinguish facilities and escape routes, but most of all speed reductions.
7.1.4 Conclusions about the cases
For the cost effectiveness of safety measures in relation to the three different types investigated, the following can be concluded:

- The differences in costs for safety measures for a Land and Immersed tunnel are very little. The choice of safety measures therefore mainly depends on the length of the tunnel, the daily traffic volume and the number of trucks transporting dangerous goods.
- The main differences in costs for safety measures for the three tunnel types, are the costs related to structural safety measures. For a Bored tunnel the structural safety measures are high compared to the other two. This means that in a cost optimisation of safety measures for a Bored tunnels, the focus should definitely be on traffic management solutions.
- Enlarging the distance between cross connections in tunnels has very little influence on the expected number of casualties and therefore is not cost effective, especially in bored tunnels, where the investments in cross connections are considerable. Though reducing the mutual distance of cross connections can help to fight the consequences of splc-accidents.
- Doubling the number of cross connections is relatively cheap for Immersed and Land tunnels, however it does not have a large impact on the safety level.
- The construction of a shoulder in the Bored tunnel is not cost effective neither with regard to the direct risk, nor when the indirect costs of traffic delay are included.
- For the Land tunnel and Immersed tunnel removing the shoulder (included in the current design) is cost effective in relation to the EV, but not in relation to the CV.
- An evaluation on the effects of a shoulder in relation to the total risk (including the indirect costs of traffic delay) shows that removing the shoulder form the current design of the Land and Immersed tunnel is cost effective.

7.1.5 Sensitivity of the input data used in the models
With respect to the sensitivity of the models on the input data, the following can be concluded:

- The daily traffic throughput, the modal split of the traffic (percentage of trucks), and the length of the tunnel, are the most important parameters that influence the safety level of a tunnel. However they are fixed parameters.
- The most efficient way to increase the safety level of a tunnel is by reducing the accident frequencies.
- The amount of dangerous cargo does not have a large influence on the safety level, while accidents with this type of transport occur with a very low probability.
- Casualties account for 80 % - 90 % of the Expected Value of the risk of tunnel accidents for the tunnel as built.
- The height of the monetary values assigned to casualties has little influence on the evaluation of cost effectiveness of the safety measures in this investigation. This is due to the fact that the cost effectiveness is regarded in relation to the tunnel as built. Changing the monetary values will also change the reference point of the investigation.
- The material risk mainly depends on breakdown accidents and normal injury accidents. Thus, the amount of damage assigned to the other categories does not have a large influence on the total material risk.
Safety measures that aim specifically at reducing the material risk, generally have little influence on the number of casualties. Their cost efficiency in relation the direct risk of tunnel accidents therefore solely depends on the relation between investments and material damage.

7.2 Recommendations

7.2.1 Further research

Below some recommendations are given for further research:

- Minimum safety levels for tunnels are not legally defined. Instead, usually the internal risk criterion is derived from the external risk criterion applicable to industrial activities (chemical industry and ports). A fixed minimum safety level for tunnels is recommended in order to reduce the never-ending discussion about safety levels.
- A complete cost efficiency investigation must include safety-mitigating measures, for instance the fire department and medical care. More research is needed to examine their influence.
- In this investigation the evaluation of the cost effectiveness of safety measures was done in relation to the reference point of the tunnel as built. It is interesting to do the same kind of cost efficiency evaluation, using an empty tunnel as reference. Though more knowledge is needed on the cumulative effects of safety measures.
- Research should be done on the parameters used in the probabilistic models regarding the escape patterns of people. The parameters used, standardize the escape procedures of people and therefore do not include the influence of the self-help of people.
- A futuristic safety measure aiming specifically on splc-accidents is the possibility of dynamic compartments, when the area of the accident is closed of from the rest of the tunnel. It is recommended to do more research on the possibilities of these systems as they might be very efficient in fighting the consequences of splc-accidents.
- The values found for the effect of regulatory safety measures vary considerably, more research is needed, since these measures appear to be very cost effective.
- An investigation on the cumulative effects of safety measures is necessary to come to a cost optimisation of the safety level in tunnels.
- It is interesting to investigate the possibilities of more pro-active measures such as, improving driving performances of people, improving the legal minimum safety properties of cars and trucks.

7.2.2 Recommendations for the Ministry of Transport

The following recommendations are for the Ministry of Transport:

- It is recommended to include injuries and material risk in the next version of the Tunprim model.
- It might be interesting to include different accident frequencies for truck and cars in the next version of Tunprim. That would enable the investigation of escorting the transport of dangerous goods.
- The current version of Tunprim distinguishes various accident frequencies (day time, rush hour and night time), however, there is still no qualitative data on the effect of traffic intensities on the accident frequencies. It is recommended to more research on this issue.
- The BOMVIT model, that includes the indirect risk of accidents, can be extended in order to evaluate more safety measures than the construction of a shoulder only.
Examining the costs of the various aspects of safety measures in tunnels (construction, installation, inspection, exploitation) is difficult because the estimations made at the various departments, do not use the same standard estimation procedure. Therefore it is recommended to move towards a standard costs estimation procedure.
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