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Evaluation of tunnel safety and cost effectiveness of measures

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ABSTRACT: Aim of this paper is to propose a framework for the evaluation of tunnel safety. Two methods for the analysis of tunnel safety, the probabilistic and the deterministic approach, and their characteristics have been described. Probabilistic criteria are proposed for the judgment of personal, societal and economic risks of tunnels. Furthermore some methods to analyse cost effectiveness of (additional) safety measures are discussed. The application of the aspects and methods discussed is illustrated with experiences and results from some practical tunneling projects.

1 INTRODUCTION

Some large accidents in tunnels in recent years, such as the fires in the Mont Blanc, Gotthard and Tauern tunnels, have lead to an increasing attention for the subject of tunnel safety. Many countries have announced additional investments in existing tunnels and the initiation of extensive studies to improve the knowledge on tunnel safety. However, absolute safety does not exist, and the possibility of a serious tunnel accident can never be completely excluded. Safety criteria have been suggested for individual tunnel projects, see for example (Geyer, 1996). And although some general target safety levels are proposed by Diamantidis et al. (2000), no commonly applicable framework is available to support safety discussions. This problem is reflected in the complicated decision making processes in many large tunnelling projects. Key points in these safety discussions are the determination of acceptable risk levels and assessment of the required investments in risk reduction measures to ensure an "optimal" safety level.

Aim of this paper is to propose some guidelines for the evaluation of tunnel safety to support these often difficult design processes. The suggested methodology can be considered as an advice to the decision makers (the politicians) from a technical point of view. The suggested criteria will deal with the problem of acceptable risk, and the optimisation of investments in safety measures in relation with economic and societal demands. The application of the framework will be illustrated with some experiences from large tunneling projects in the Netherlands.

Firstly, two approaches for the analysis of tunnel safety, the probabilistic and deterministic approach, are analysed in section 2. In section 3 a framework for the evaluation of tunnel safety is proposed. Section 4 focuses on the analysis of cost effectiveness of life saving measures. Some of the aspects that are brought forward are illustrated with results from some practical case studies in section 5. Section 6 contains the conclusions of this study.

2 PROBABILISTIC VS DETERMINISTIC APPROACH OF TUNNEL SAFETY

In the analysis of tunnel safety both probabilistic and deterministic analyses are carried out.

The **probabilistic analysis**, or the quantitative risk analysis (QRA), is based on an inventory of all possible accident scenarios. The potential accidents can be shown in a so-called event tree, which outlines possible events after occurrence of the accident. Probabilities and consequences (e.g. fatalities, economic damage) of all these scenarios have to be estimated and combined in a risk number, for an example an FN curve or an expected number of fatalities. If the costs of measures to reduce the probability or consequences of an

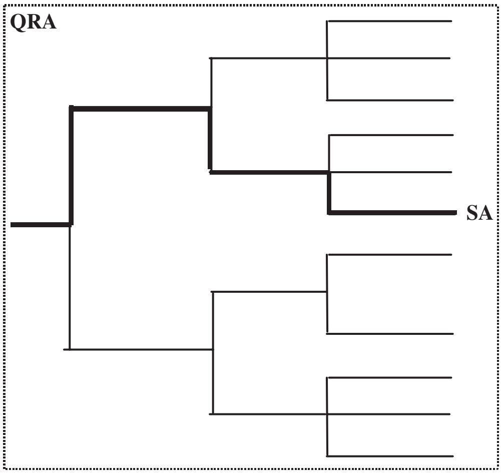

Figure 1. Schematic difference between probabilistic (QRA) and deterministic analysis (SA).

accident are known, an implicit or explicit optimisation can lead to a decision on the level of protection and consequently to accepted level of risk.

The **deterministic** or scenario analysis (SA) focuses on the analysis of processes during one accident scenario and the outcomes of this scenario are used as input for design and decision making. A detailed analysis of accident scenarios (as is carried out in a deterministic analysis) will provide more insight in the processes during the accident, the possibilities for the rail/road user to escape in the event of a disaster (self-rescue), as well as the provision of aid by the public emergency services.

The difference between the probabilistic and deterministic analysis is shown in Figure 1. The whole imaginary event tree in the figure forms the basis for a probabilistic analysis. Each branch of the event tree represents one accident scenario. The bold line shows one (random) accident scenario which will be analysed in a deterministic analysis. In the deterministic analysis the probability of occurrence of the accidents is generally not taken into account.

A possible problem of the use of solely the deterministic analysis in deciding on desired levels includes the selection of an overly risky (or safe) scenario. This will provide overly negative (or optimistic) information to the decision maker and will force him to choose extreme (or too little) safety measures. The result of this decision making can be that society discovers during the implementation or use of the structure that indeed extreme measures have been chosen and that the costs are out of proportion. The final optimisation will then be the result of a trial and error process, in which policy making will be triggered by accidents, and not of thinking in advance.

Therefore the probabilistic analysis is most suitable for the evaluation of tunnel safety. It takes into account all relevant scenarios and thus ensures a balanced decision making. The benefit of the risk based approach is that different kinds of measures can be judged for their safety merits. The reduction of accident probabilitis caused by preventive measures can be compared with the reduction of consequences resulting from mitigating measures. The main problem in the application of the probabilistic analysis is the determination of acceptable risk levels. However, also the deterministic analysis of accident scenarios can prove a useful additional tool for a more detailed consideration of certain aspects such as the possibilities of self rescue and the demands for emergency services.

3 SUGGESTED FRAMEWORK FOR THE EVALUATION OF TUNNEL SAFETY

In the previous section it has been stated that the evaluation of tunnel safety should be mostly based on probabilistic evaluation of safety levels. A set of probabilistic criteria is suggested in section 3.1. Also the value of a deterministic approach has been recognized and section 3.2 discusses some aspects of the deterministic approach, such as the choice of a representative design scenario and the need for additional safety measures.

3.1 *Probabilistic risk assessment framework*

Based on previous research (Vrijling, 1998) a set of rules is presented for the judgment of personal, societal and economic risk for tunnels. The three approaches should all be investigated and presented. The most stringent of the three criteria should be adopted as basis for the "technical" advice to the political decision makers.

3.1.1 *Personally acceptable level of risk*

The first criterion is concerned with the personal level of risk. Although many, slightly different definitions are in use for the personal or individual risk, they are all concerned with probability for the individual of losing one's life. In the case of tunnels two types of parties at risk can be distinguished. Internal parties are persons who are at risk in the tunnel, the users for road tunnels, the passengers and employees for railway tunnels. External parties are the persons living in the area of tunnel. Since all these parties will have different relations with and various attitudes towards the hazards resulting from the presence of the tunnel, different risk levels can be considered acceptable for them.

A criterion for the acceptable individual risk (IR) is proposed by Vrijling et al. (1998), which takes into account the degree to which the activity is voluntary, and the benefit perceived.

$$IR < \beta \cdot 10^{-4} \left(yr^{-1} \right) \qquad (1)$$

Table 1. Proposed β values for different parties involved in tunnel safety.

	Party	β
Internal	Employees (rail)	1
	Passenger or user	0.1
External	Persons living near the tunnel	0.01

where:
β policy factor, varies according to the degree to which participation in the activity is voluntary and with the perceived benefit.

In Table 1 β values have been suggested for the parties involved in tunnel safety based on Vrijling (1998).

3.1.2 *Socially acceptable risk*

While the former section deals with risks from point of view of the individual, it should also be considered from a social point of view. Societal risk is concerned with the probability that a whole group of people will be killed due to an accident with a certain probability of occurrence.

Societal risk is often represented graphically in a FN-curve. This curve displays the probability of exceedance as a function of the number of fatalities, on a double logarithmic scale. Also the expected values of the number of fatalities (which equals the surface under the FN curve) is often used. An important aspect in the societal judgment of hazardous activities are the "small probabilities – large consequences" accidents. The expected value is generally very low for this type of accidents (as are tunnel accidents) and therefore does not seem a good risk measure for tunnels. The standard deviation of the number of fatalities is relatively high for these types of accidents. Therefore, the so-called characteristic value is proposed as a suitable measure for societal risk. It consists of the expected value of the number of fatalities and the standard deviation, which is multiplied by a risk aversion factor k, for which a value of $k = 3$ is proposed based on the analysis of several activities in Vrijling (1995):

$$E(N) + k \cdot \sigma(N) \tag{2}$$

The total risk takes a risk aversion index k and the standard deviation into account and is therefore called risk averse. The following limit, which again takes into account the policy factor β, is proposed to limit risks on a national level:

$$E(N) + k \cdot \sigma(N) < \beta \cdot 100 \tag{3}$$

It has been shown (Vrijling, 1998) that this national criterion for acceptable risk can be translated into a standard for a single (tunnel) location. This criterion has the typical form of a FN limit (with a quadratic steepness):

$$1 - F_N(x) < \frac{C}{x^2} \tag{4}$$

where:
$1-F_N(x)$ probability of more than x fatalities per year
C constant that determines the position of the FN limit line

Suppose that the expected value of the number of fatalities is much smaller than its standard deviation (which in general is true for accidents with low probabilities and large consequences) and assume a Bernoulli distribution of the number of fatalities. The factor C can now be written as a function of the number of installations on a national level (N_A), the risk aversion factor (k), and the policy factor (β):

$$C = \left[\frac{\beta \cdot 100}{k \cdot \sqrt{N_A}}\right]^2 \tag{5}$$

For applications for tunnel safety again the distinction can be made between internal users (or employees) and external parties. Considering the differences between these parties, different standards should be applied for these parties, and different β's are applicable for them, see Table 1 for suggested values. The finally chosen height of the limit will also depend on the number of installations. In the derivation of the local limit, first the acceptable risk should be set on the national level. Consequently, the acceptable risk should be distributed over the tunnel locations. Since no risk limit for tunnels has been established on a national level yet, often safety criteria applied in other tunnelling project are used as reference values (see also section 5 for an overview).

3.1.3 *Economic optimisation*

The derivation of the (economically) acceptable level of risk can also be formulated as an economic decision problem, as has been shown by van Danzig (1956) for flood defences. According to the method of economic optimisation, the total costs in a system (C_{tot}) are determined by the sum of the expenditure for a safer system (I) and the expected value of the economic damage ($E(D)$). In the optimal economic situation the total costs in the system are minimised:

$$\min(C_{tot}) = \min(I + E(D)) \tag{6}$$

With this criterion the optimal probability of failure of a system can be determined, provided investments (I) and the expected economic damage ($E(D)$) are a function of the probability of failure. For tunnels investments can be done in safety measures to prevent or mitigate damage D. The economic damage can consist of the direct losses of the tunnel construction and it's installations (i.e. the investments to rebuild them) and indirect damage due to the loss of the transport connection of which the tunnel is part. When the probabilities of the different accident scenarios are known the expected economic damage can be assessed, and an economically optimal level of protection can be derived. In addition to the determination of the optimal level of protection it should be investigated whether the project generates economic benefits for society, i.e. whether the total costs in the optimal situation are smaller than the total costs in the economic optimum.

In tunnel safety an important consequence is the potential loss of life for certain accident scenarios. It is possible to take the value of human life into the economic optimisation. Assume that a certain scenario will result in N fatalities and that every person has an economic value d. For the valuation of human life for example the present value of the nett national product per inhabitant is proposed. The economic optimum can again be found by minimising the total costs:

$$\min(C_{tot}) = \min(I + E(D + N \cdot d)) \tag{7}$$

The valuation of human life may raise numerous ethical and moral questions, because some people consider life invaluable. It can thus be easily understood that not taking into account the economic value of human life in the economic optimisation will lead to lower expected damages and thus to lower optimal safety levels. Experience shows that the influence of loss of life is relatively limited in an economic analysis. Therefore separate criteria for limitation of the risk of loss of life have been proposed above.

3.2 *Deterministic approach: representative design scenarios and additional measures*

Based on the probabilistic approach a tunnel design can now be chosen applying the rules as described above. The tunnel design will now comply with the standards for individual and societal risk. Furthermore the design will be optimised from an economic point of view.

In addition to the probabilistic approach also a scenario analysis should be performed. This deterministic analysis provides more insight in the accident processes and focuses on the optimisation of self rescue and emergency assistance. Also standards can be formulated for deterministic scenarios: for example the allowable time for all passengers to have left the tunnel in case of a train fire.

A problem in the deterministic analysis is the choice of a representative scenario. In section 2 it has been described how the selection of a representative design scenario without consideration of the probability of occurrence can lead to inconsistent decision making. Theoretically, a design scenario can be derived with the method of economic optimisation, as will be shown in a (simplified) example. Assume a tunnel in which one type of accident can happen with probability p_1, causing damage D_1. In calculation of the economic risk the discount rate r is applied. Assume a function in which investments increase as a function of the negative logarithm of the probability of that accident $-ln(p_1)$ with a steepness of I_1'. The total costs (C_{tot}) can now be written as:

$$C_{tot} = I'_1 \cdot -\ln(p_1) + p_1 \cdot D_1 / r \tag{8}$$

The optimal system failure probability (p_{opt}) can be derived as follows.

$$dC_{tot} / dp_1 = 0 \quad p_{opt} = I'_1 \cdot r / D_1 \tag{9}$$

The representative design scenario is the scenario which occurs with a probability of p_{opt}. When two types of accidents (type 1 and 2) can occur independently, the total costs are (equation 10):

$$C_{tot} = I'_1 \cdot -\ln(p_1) + I'_2 \cdot -\ln(p_2) + p_1 \cdot D_1 / r + p_2 \cdot D_2 / r \tag{10}$$

The optimum can be found as follows.

$$\begin{aligned} &dC_{tot} / dp_1 = 0 && p_{opt1} = I'_1 \cdot r / D_1 \\ &dC_{tot} / dp_2 = 0 && p_{opt2} = I'_2 \cdot r / D_2 \\ &p_{opt} = p_{opt1} + p_{opt2} \end{aligned} \tag{11}$$

When the two scenarios are fully dependent the following optimum will be found:

$$p_{opt} = \max(p_{opt1}, p_{opt2}) \tag{12}$$

In these cases it is recommended to choose scenarios which dominate this optimum as representative design scenarios (i.e. the scenarios which have the highest contribution to the optimal probability). Also it is possible to select more representative design scenarios, as is often done in practice. However, in practice the optimisation functions and the determination of the representative design scenario will be more complex. It is easily understood that the assumption of a linear investment function is quite unrealistic. Costs will for example increase dramatically when the decision is made to construct a second tunnel tube to prevent frontal collisions. Also the assumption of independence of scenarios can be questioned. The large disastrous accidents initially start with a small disruption of the regular situation, and thus the various scenarios will be linked. Also the effect of preventive measures will not be limited to one type of accidents, but result in risk reduction for more types of accidents.

Consider a tunnel which complies with the probabilistic safety criteria as mentioned in section 3.1. A possible outcome of the deterministic analysis could be that extra measures are advisable to limit the impacts of certain accidents. These are defined here as additional measures. Experiences from tunnelling projects in the past have shown that based on deterministic considerations measures have been chosen in the design which would not be necessary from a strictly probabilistic point of view. To facilitate decision making concerning additional measures some principles are proposed here. First of all the costs of additional measures should be reasonable in comparison with the total project costs. This criterion can be fulfilled by requiring that the investments on additional measures should amount no more than a certain percentage of the total project costs. Further study on the expenses on additional measures for different tunnelling projects could reveal the order of magnitude of this fraction.

Furthermore the effectiveness of the additional measure should be explicitly taken into account in the decision making processes. This requires that is not merely said that a tunnel is to be designed with optimal efficiency. Costs of investments and their risk reducing effects should also be explicitly quantified. The subject of cost effectiveness of measures in relation with the reduction of risk of human life loss is discussed in the next section.

4 COST EFFECTIVENESS OF SAFETY MEASURES

A large part of the investments in tunnels is concerned with the reduction of potential loss of life, either by reducing the probabilities of accidents or by reducing the consequences of accidents. The subject of cost effectiveness of investments in relation with reduction of fatalities is thoroughly studied for many sectors in literature, however relatively little is known of this subject for tunnels. One important approach relates the value of human life to the investment made and to the number of prevented fatalities. The cost of saving an extra life (CSX) expresses the investment made for saving one extra (statistical) life. The investment is generally related to the (reduction of) the expected number of fatalities:

$$CSX = I / \Delta E(N) \tag{13}$$

It has been shown by Vrijling and van Gelder (2000) how the cost of saving a human life per year (related to the expected value) can be determined from the economic optimisation. The costs of saving an extra life year (CSXY) can be calculated by involving life expectancy in this method. An extensive study of CSXY values in various sectors, carried out by Tengs et al. (1995), showed that CSXY values vary widely across different sectors.

However, in the case of rare accidents with large consequences the expected value of the loss of life will be small. Involving this low expected value in the calculation of cost effectiveness does not reflect the social aversion against these types of accidents (e.g. airplane crashes, large tunnel accidents). A characteristic of this type of accidents is that standard deviation will be relatively high. Therefore it can be considered to use the characteristic value (which includes the standard deviation) in determination of cost effectiveness (instead of the expected value):

$$CS_{E(N)+k\cdot\sigma(N)} = I / \Delta(E(N) + k \cdot \sigma(N)) \tag{14}$$

In the two cases mentioned above statistical or probabilistic information is used. However, a deterministically oriented decision maker will be more interested in the reduction of loss of life for a certain accident scenario, regardless of the probability of occurrence. From a deterministic point of view, cost effectiveness can now be related to the number of fatalities prevented for a certain accident scenario.

$$CS_N = I / \Delta N \tag{15}$$

Consider now the following example: It is proposed to install a sprinkler system in the tunnel. The costs of the sprinkler are Euro 20 million and it will prevent the occurrence of a serious accident (for example an explosion) which has a probability of occurrence of 10^{-5} per year and which will cause an estimated 100 fatalities. The probabilistic decision maker (for example the risk analyst) relates the investment to both expected and characteristic value.

$$E(N) = p \cdot N = 10^{-5} \cdot 100 = 10^{-3}\, fat/yr \quad \sigma(N) = \sqrt{p} \cdot N = 0{,}31\, fat/yr$$

$$TR = E(N) + k \cdot \sigma(N) = 0{,}95\, fat/yr$$

$$CSX = I / \Delta E(N) = 20 \cdot 10^{9}\, Euro/fat/yr$$

$$CS_{E(N)+k\cdot\sigma(N)} = I / \Delta(E(N) + k \cdot \sigma(N)) = 21 \cdot 10^{6}\, Euro/fat/yr$$

The risk analyst concludes that when the expected value is considered, the sprinkler should not be installed. When risk aversion is considered, as is done with the characteristic value, the investment might be an option, but still one at high cost. The final decision will depend on the available budget, and the preferences of the final decision maker.

The deterministic decision maker will relate the investment, regardless of the probability of occurrence of the accident to the number of fatalities prevented. From this (deterministic) point of view it can be concluded that this investment might be a good option.

$$CS_N = I / \Delta N = 200.000\, Euro$$

Although, this example concerns a theoretical case, it is a good illustration of the discussions which have occurred between different stakeholders in some large tunnelling projects in the Netherlands.

4.1 *Application of cost effectiveness of measures in decision making*

Before performing an analysis of cost effectiveness, it should first be analysed whether the tunnel complies with the decision criteria presented in section 3.1. A cost effectiveness analysis should be carried out to decide on the additional level of measures which can be achieved at reasonable cost. The analysis can thus used in applying the well known ALARA principle. Since the additional measures are linked to risk levels, determination of the cost effectiveness of measures in relation to life safety should be based on a probabilistic analysis. Costs of additional measures can be weighed against the risk reduction. The typical relation between investments and risk levels is plotted in Figure 2. The figure shows that the incremental costs of reducing risk increase as the risk becomes smaller (Bohnenblust, 1998).

Depending on the preferences of the responsible decision maker expected value ($E(N)$) or characteristic value (or another probabilistic risk measure) can be chosen as the unit for risk. It should be noted that the function is plotted as a continuous line, but in practice it will have a more stepwise form. Consider for example decisions such as the construction of second tube or the installation of a sprinkler installation. The optimal risk reduction curve is formed by the measures resulting in the largest risk reduction with the smallest investments. This method offers the possibility to compare various alternative measures for their cost effectiveness (for example: heat resistant lining vs. sprinkler). Also a comparison between different projects and sectors can be made. Economic efficiency requires that the marginal benefits per Euro spent should be equal for various investments across different sectors (Tengs et al., 1998).

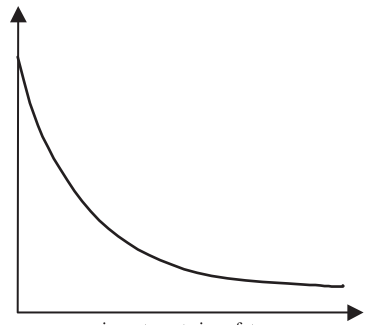

Figure 2. Relation between investments in safety measures and risk levels.

5 CASE STUDIES: APPLICATION OF THE FRAMEWORK

This section will illustrate the application of the framework presented in section 3 and the analysis of cost effectiveness as discussed in section 4. Some information from recent tunnelling projects in the Netherlands has been investigated, and where no figures were available some fictive examples have been given.

5.1 *Individual and social risk*

Criteria for individually and socially acceptable risk are commonly applied in tunnelling projects in the Netherlands. An overview of the standards applied for the judgment of internal risks for a few tunnels in the Netherlands is given in Table 2.

The personally acceptable risk can be presented as the probability of death per kilometre travelled per year or the probability of losing life for an average user or employee. It is calculated as the probability of losing one's life for the "average" user or employee of the tunnel. For the judgment of societal risks both FN limits and limits for the characteristic value have been proposed.

For the external risks near tunnel locations an acceptable personal risk of 10^{-6} per year and an acceptable societal risk of $10^{-2}/N^2$ are applicable in the Netherlands (Tweede Kamer, 1996).

5.2 *Economic optimisation*

Although "optimal" safety is often stated to be an important aim in design processes, no direct practical application of the method of economic optimisation can be presented. Therefore a case study is presented below.

Table 2. Overview of safety standards applied in some projects (Molag, 2002).

		Tunnel		
		HSL	Western Scheldt	Betuwe
PR	Users/ passengers	$1.5 \cdot 10^{-10}$ /km/yr	$1 \cdot 10^{-10}$ /km/yr	–
	Employees	$5 \cdot 10^{-5}$/yr	–	$5 \cdot 10^{-5}$/yr
GR	F_N	$4 \cdot 10^{-2}$ $/N^2$/yr/km	10^{-2} $/N^2$/yr/km	10^{-2} $/N^2$/yr/km
	Char. Value	2.3 fat/yr	–	–

Consider the following simplified example of the design of a tunnel system. A decision maker has to choose between two design alternatives: a single and a double tube tunnel. Two types of accidents can occur: a frontal collision (only in the single tube) and an accident in which a truck catches fire within the tunnel system. The following decision tree can now be made as shown in Figure 3.

The economic optimisation is applied to decide on the necessity of certain measures. Assume that the probability of a truck fire is known for both alternatives: $p_2 = 0, 1$ and that r = 0.05. The total costs can now be determined as follows for both tunnels:

$$C_{tot1} = 1000 + p_1 \cdot 100/r + p_2 \cdot 200/r$$
$$= 1400 + p_1 \cdot 2000$$

$$C_{tot2} = 2000 + p_1 \cdot 0 + p_2 \cdot 100/r = 2200$$

Thus only if the probability of a frontal collision $p_1 \geqslant 0.4$ per year, a double tube tunnel is economically optimal. However, also human life is involved in these accidents. This value can be included in the economic optimisation as is shown in section 3.1. Assume a value of the human life of 1 million Euro. Again a similar analysis can be carried out.

$$C_{tot1} = 1000 + p_1 \cdot (100 + 10)/r + p_2 \cdot (200 + 20)/r$$
$$= 1440 + p_1 \cdot 2200$$

$$C_{tot2} = 2000 + p_1 \cdot 0 + p_2 \cdot (100 + 10)/r = 2220$$

If the loss of human life is included then a probability of frontal collision of $p_1 \geqslant 0.35$ per year, will already point to a double tube as economically optimal. Experience shows that the influence of loss of life is relatively limited in an economic analysis.

Western societies place however implicitly a greater value on human life than explicitly. This leads to separate reasoning for the acceptable levels of individual and group risk and a relatively strong preference for double tube tunnels.

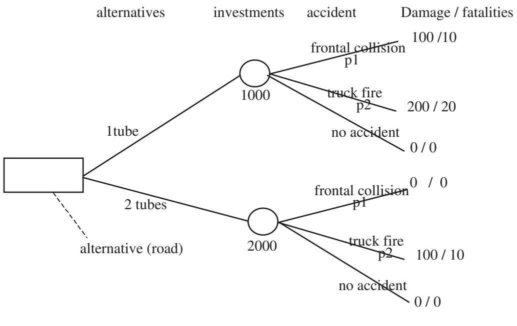

Figure 3. Decision tree for the tunnel example (costs in millions of Euros).

5.3 *Cost effectiveness*

An estimation of cost effectiveness has been made for two practical cases in the Netherlands. The first is a tunnel which is constructed near the city of Roermond as part of the A73 highway. It is constructed as a double tube tunnel (2 × 2 lanes) with a length of 3260 m. The second example considers a feasibility study which is undertaken on the construction of a seven kilometre long double tube tunnel (2 × 3 lanes) to connect the two Junctions of the A6 and A9 highways near Amsterdam. Both are so-called category 0 tunnels, which means that no limitations for the transport of dangerous goods are applicable.

Now the cost effectiveness of the installation of a sprinkler system is investigated for these two tunnels. Many international studies have been published on the effectiveness of sprinkler systems. In the simplified approach in this study the risk reducing effects of the sprinkler system are estimated as follows. It can prevent a so-called "hot BLEVE", a BLEVE (gas explosion) which occurs after some time when the contents of a fuel tank have been heated sufficiently. The sprinkler system can not prevent an instantaneous explosion or BLEVE. Since little is known about the mitigating effects of sprinklers for tunnel fires, this effect is not taken into account (in fact: some authors argue that the use of sprinklers in case of an accident can increase the risks since large amounts of steam will be developed). Based on experience data the costs of the sprinkler system are roughly estimated at 10 million Euro/km tunnel.

The risk reducing effects of the installation of the sprinkler system have been analysed with the Tunprim model (de Weger, 2001). With this quantitative risk analysis model the internal risks for the users have been assessed. The FN curves for both tunnels, with and without sprinkler system, are shown in Figure 4. Moreover expected value ($E(N)$ = area under the FN curve) and characteristic value have been determined. The figures only show the FN curves for the small probability – large consequences events, such as BLEVEs and large fires. Experience shows that expected value is to a large degree determined by collision accidents without fire of explosion. In Table 3 cost effectiveness is related to the expected value and the characteristic value.

The presented risk calculations are just indicative results for these examples, and can not be seen as officially determined risk levels. However, from the figure and the table it can be seen that the sprinkler does have a minor influence on FN curves and expected value of the number of fatalities. It can also be concluded that the investments in a sprinkler installation for these cases

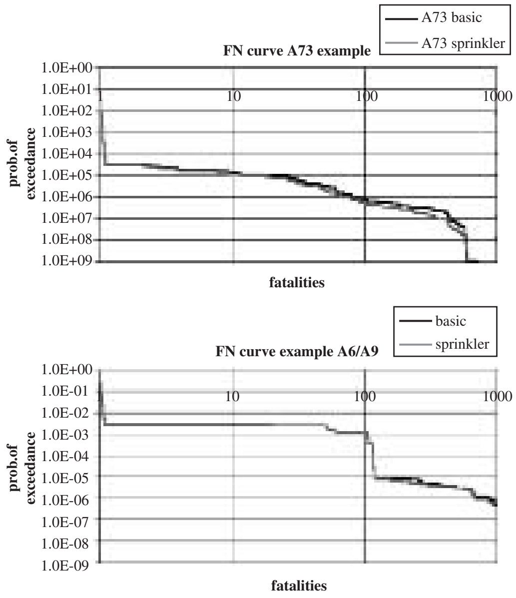

Figure 4. FN curves with and without sprinkler for the A73 example and the A6/A9 example for the small probability large consequences accidents.

Table 3. Cost effectiveness figures for the installation of a sprinkler system.

			Expected value (fat/yr)	
Tunnel	Length	Estimated cost of sprinkler	Basic	Sprinkler
A6/A9	7000	$7 \cdot 10^7$	1.9189	1.9179
A73	3260	$3 \cdot 10^7$	0.1103	0.1101

	Characteristic value (fat/yr)		Cost effectiveness (Euro/(fat/yr))	
Tunnel	Basic	Sprinkler	*CSX*	$CS_{E(N)+k.\sigma(N)}$
A6/A9	16.1	15.7	$7 \cdot 10^{10}$	$1.75 \cdot 10^8$
A73	1.44	1.32	$1.5 \cdot 10^{11}$	$2.5 \cdot 10^8$

are not preferable when cost effectiveness is considered from a probabilistic point of view. From the two examples it can be seen that the cost effectiveness of the sprinkler system are in the same order of magnitude: about 10^{11} Euro/fatality per year when related to the expected value and about $2 \cdot 10^8$ Euro per fatality per year when related to the characteristic value. This can partly be explained by the fact that the same QRA model with the same assumptions is used in the calculations for the two tunnels. An investigation for other tunnels and measures should reveal whether cost effectiveness figures are still in the same order of magnitude for other cases.

6 CONCLUSIONS

Aim of this paper is to propose some guidelines for the evaluation of tunnel safety. Two methods for the evaluation of tunnel safety have been analysed, the probabilistic and the deterministic approach. It can be concluded that the application of solely a deterministic analysis can lead to inconsistent decisions and that the probabilistic risk analysis should be the basis for the design of the tunnel. The deterministic or scenario analysis can be applied as an additional tool to provide more insight in the accident processes, the possibilities for self rescue and emergency assistance.

A (probabilistic) framework has been proposed for the judgment of personal, societal and economic risks of tunnels. The three criteria should all be investigated and presented. The most stringent of the three should be adopted as basis for the "technical" advice to the political decision makers. Cost effectiveness of measures should be analysed based on probabilistic information. Some methods to analyse cost effectiveness from different points of view have been discussed.

An analysis of the application of elements of the framework proposed in practical situations has shown that standards for limitation of personally and socially acceptable risk are commonly applied in tunneling projects in the Netherlands. A simplified example of economic optimisation of a tunnel shows that a method can be applied to determine the optimal level of safety in the tunnel, from an economical point of view. Two case studies for an existing and a planned tunnel have shown that cost effectiveness of the installation of a sprinkler system is very low for the studied examples. The derived cost effectiveness numbers for the two examples are of the same order of magnitude. Further study should indicate whether the cost effectiveness figures for other tunnels also show a similar pattern.

Although this paper does not provide full solutions for the complicated safety discussions in tunnelling projects, it is the hope of the authors that these ideas might contribute to a more rational and efficient decision making on the investments in tunnel safety.

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