Evaluation of tunnel safety: towards an economic safety optimum

B.J. Arends[a,b], S.N. Jonkman[a,b,*], J.K. Vrijling[a], P.H.A.J.M van Gelder[a]

[a]Section of Hydraulic Engineering, Faculty of Civil Engineering, Delft University of Technology, Delft, The Netherlands
[b]Civil Engineering Division, Centre for Tunnel Safety, Rijkswaterstaat, Ministry of Transport, Public Works and Water Management, Utrecht, The Netherlands

Abstract

The aim of this paper is to propose a method for the evaluation of tunnel safety using probabilistic risk assessment. The framework includes three criteria; personal-, societal- and economic risk. The use of personal and societal risk is becoming more and more widespread. There are however, still some difficulties in using the economic risk criterion. As a first step towards economic risk optimisation, the cost effectiveness of addition and removal of safety measures in tunnels is investigated. Finally, the application of the three proposed criteria is further discussed for some tunnelling projects currently underway in the Netherlands.
© 2005 Elsevier Ltd. All rights reserved.

1. Introduction

Some large accidents in tunnels in recent years, such as the fires in the Mont Blanc, Gotthard and Tauern tunnels, have led 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 [1–3]. And although some general target safety levels are proposed [4], 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 an acceptable risk level on one hand, and the amount of investments in and the effectiveness of the risk reduction measures, needed to achieve this level, on the other. Safety thereby becomes a highly political issue. Because studies in

other fields have shown that the actual investments in safety do not always result in a minimisation of risk [5], it is essential that we first investigate the cost effectiveness of safety measures in tunnels.

Aim of this paper is to set up a framework for the evaluation of the safety level of tunnels. Three criteria are discussed that can be used to achieve a clear definition of an acceptable risk level. They include the personal risk, societal risk and finally the economic risk as a result of tunnel accidents.

There is some experience in the field of evaluating personal- and societal risks. Although there is substantial experience throughout Europe in the economic assessment of prevention of accidental fatalities (see e.g. [6]), the experience in assessing tunnel risks from an economic point of view is limited [7]. Some issues justify a specific analysis of investments in tunnel safety, as the considered measures will have different characteristics than the measures applied in road safety. The investments in tunnel safety concern relatively higher costs (e.g. of ventilation, sprinkler installations) and they are often related to the prevention or mitigation of accidents with small probabilities and large consequences, such as fires and explosions.

As a first step a method to analyse the cost effectiveness of individual safety measures for tunnels is described. Eventually, this will clear the way for a complete economic optimisation of risks related to tunnels.

* Corresponding author. Address: Civil Engineering Division, Centre for Tunnel Safety, Rijkswaterstaat, Ministry of Transport, Public Works and Water Management, Utrecht, The Netherlands.
E-mail address: s.n.jonkman@dww.rws.minvenw.nl (S.N. Jonkman).

Firstly, the theory of the probabilistic risk assessment of tunnel safety is discussed in Section 2. Section 3 focuses on the presentation of the consequences of tunnel accidents in financial terms. The current constraints with applying the traditional framework of economic risk optimisation to the evaluation of tunnel safety are discussed in Section 4. In the same section, a method is discussed to investigate the cost effectiveness of safety measures. Some of the aspects that are brought forward are illustrated with results from practical case studies in Section 5. Finally, Section 6 contains the conclusions of this study.

2. Probabilistic approach of safety

There are several methods in use to evaluate the safety level of a tunnel. The ones most commonly used are the deterministic and the probabilistic approach. A deterministic (or scenario) analysis focuses on one or a few design scenarios and their development from the normal situation into a large-scale accident. The effectiveness of safety measures can then be investigated on the basis of their influence on the development of these scenarios. Furthermore, deterministic criteria can be proposed for the functioning of several elements, for example for the capacity of emergency exits, or the performance of emergency services. Although deterministic analyses focus on the effects and consequences of an accident, the notion of probability is often implicitly accounted for in the selection of design scenarios.

However, to compare the safety level of various tunnels and for the investigation of the cost effectiveness of safety measures, the risks can be best investigated using probabilistic risk analysis. The probabilistic analysis, or the quantitative risk analysis (QRA), is based on an inventory of all possible accident scenarios. A so-called event tree is made from all events that can occur during the use of the tunnel Fig. 1. This event tree includes, besides the normal situation, also every disturbance in the tunnel and its

possible consequences. Consequences are normally expressed in fatalities and injuries, but can also include economic damage (e.g. to the tunnel and vehicles, or traffic delay). When both the probability and the consequences are assigned to every branch of the event tree, one is able to present the risk level of a tunnel as the sum of all probabilities times their consequences. While risk itself is dimensionless, the risk level is presented in the dimension of the consequences (e.g. the number of fatalities or injuries, or in financial terms). If the costs of measures to reduce the probability or consequences of an 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. Note that the deterministic and probabilistic approaches are complementary as the deterministic analysis focuses on one of the scenarios investigated in the probabilistic analysis.

A set of rules is presented to judge the risk level in general, using three criteria: personal-, societal-, and economic risk. The first criterion is considered with the personal level of risk. When the personal risks are considered acceptable the aggregated level of risk on a national or local scale could still be considered unacceptable. Therefore a societal risk criterion is needed. Finally, (aspects of) the problem the acceptable level of risk can be formulated as an economic decision problem. The three criteria (further discussed below) must all be investigated and presented during the design of a tunnel. The most stringent of the three criteria should be used as the minimum risk level per unit time for the tunnel. A further discussion and justification of this set of rules is given in [8,9].

2.1. Personal acceptable risk level

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 the probability for the individual of losing one's life. In the case of a tunnel 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 vicinity of a 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 in [8], which takes into account the degree to which the activity is voluntary, and the benefit perceived.

$$\text{IR} < \beta 10^{-4}(\text{yr}^{-1}) \tag{1}$$

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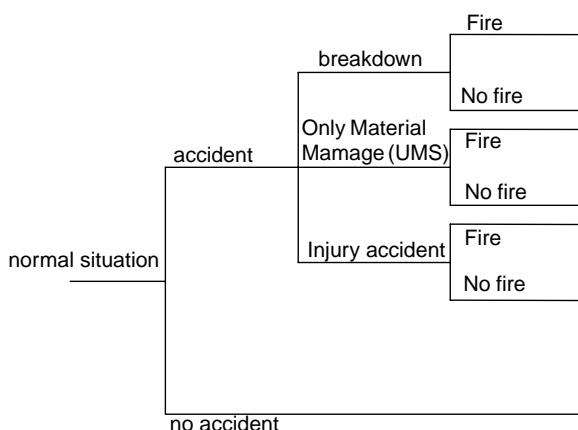

Fig. 1. Simplified example of the start of an event tree used in a QRA.

	Party	β	Individual risk (yr^{-1})
Internal	Employees (rail)	1	10^{-4}
Internal	Passenger or user	0.1	10^{-5}
External	Persons living near the tunnel	0.01	10^{-6}

Table 1 gives some suggestions for β values for the parties involved in tunnel safety. Although the β values proposed in [8] are derived from statistics on accidents, we note that the choice of the value of policy factor is subjective. Therefore, agreement on the appropriate level of β has to be achieved in the decision making process. The risk limits in Table 1 correspond to those used for the judgement of the risks of the transport and storage of hazardous materials in the Netherlands.

2.2. Social acceptable risk level

The second criterion is the social acceptable risk, which takes into account the social adversity of large-scale accidents, especially when they involve high amounts of casualties. Societal risk is often represented graphically in the form of a FN-curve. This curve displays the probability of exceedance of a certain number of fatalities, on a double logarithmic scale. An important aspect in the societal judgment of hazardous activities are the 'small probabilities large consequences' accidents (or in short: 'splc-accidents'). An FN-curve gives a clear representation of the probability of this kind of accident.

Also, the expected value of the number of fatalities $(E(N))$ is often used, which equals the surface under the FN curve. However, the expected value is generally very low for 'splc-accidents' and therefore the expected value does not seem to be a good risk measure for this type of accidents. Though, the standard deviation of the number of fatalities is relatively high, for this type of accidents. Therefore, the so-called characteristic value (CV) is proposed as a suitable measure for societal risk [8]. This value includes not only the Expected Value of the number of fatalities, but also its standard deviation, which is multiplied by a risk aversion factor k. The height of k determines the level of adversity. For risk assessment of tunnel safety, a value of $k=3$ is proposed based on the analysis of several activities [9].

$$CV = E(N) + k\sigma(N) \quad (2)$$

The following limit, which again takes into account the policy factor β, is proposed to limit risk on a national level:

$$E(N) + k\sigma(N) < \beta \times 100 \quad (3)$$

It has been shown [8] 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):

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

where:
$1 - F_N(x)$ probability of more than x fatalities per year[1]
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):

$$C = \left[\frac{\beta 100}{k\sqrt{N_A}}\right]^2 \quad (5)$$

When applied to 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 choice of the 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. The choice of the acceptable risk level on a national scale will reflect national choices and preferences. We note that the use of local risk standards (only) can lead to an undesirable situation on a national scale. An increase in the number of installations, each of them acceptable according to the local limit, can lead to an unacceptable high-risk level on a national scale [8]. No risk limit for tunnels has been established on a national level yet. Therefore, the safety used criteria in other tunneling projects are often used as reference values in the derivation of risk standards for new projects.

2.3. Economic risk optimum

The third and final risk criterion is the economic criterion, which aims at an economic optimisation of the risk level. The investments in safety are weighed against the remaining risk level. A well-known derivation of such an economic acceptable level of risk was formulated by Van Dantzig in 1956 for flood defence systems [10].

---

[1] Note that a different convention can be found in other published works, in which the symbol $F_N(x)$ (or $F(x)$) signifies the probability of 'x or more' fatalities per year.
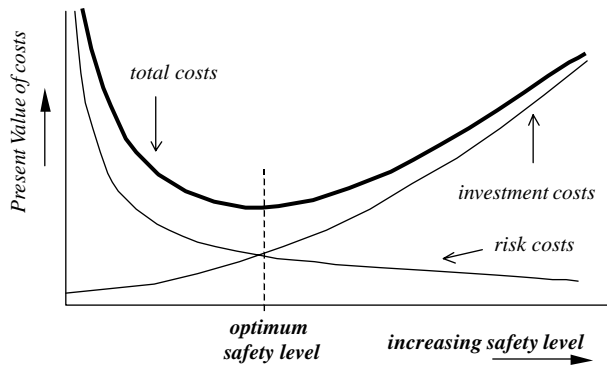
Fig. 2. Schematic representation of the economic risk optimisation used for according to Van Danzig.

According to Van Dan zig's 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:

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

With this criterion the optimal probability of failure of a system can be determined, provided that the investments (I) and the expected economic damage ($E(D)$) are a function of the probability of failure. A simplified graphic representation of such a cost optimisation is given in Fig. 2. The figure shows that the incremental costs of reducing risk increase as the risk becomes smaller, also see [11]. The other line shows a rough estimation of the risk costs as function of the level of safety. It can be seen that the sum of both risk costs and investments has a minimum, representing the optimum safety level.

This economic risk optimisation has proven to be a very effective way for the definition of the optimal risk level of the flood defence system in the Netherlands. Therefore, an effort is made to apply this framework to find an economic risk optimum for tunnels (discussed in Section 4).

3. Economic valuation of the consequences of tunnel accidents

In an economic evaluation of risk the consequences of tunnels accidents have to be presented in financial terms. This is a straightforward exercise for the damage that is directly related to the damage or loss of the tunnel and its equipment, and the damage to the vehicles. When taking into account other consequences of tunnel accidents, such as injuries or the loss of life, this proofs to be a more difficult task. An approach would then be to assign a monetary value to the casualties that result from an accident. This may raise ethical and moral questions, but it is necessary in an economic evaluation and brings consistency in the decision process [7]. Moreover, it can be easily understood that

neglecting the economic value of loss of human life in the economic optimisation will lead to lower expected damages and thus to a lower optimal safety level. Finally, the economic costs of traffic delays as a result of a temporary closure of the tunnel can be taken into consideration to come to a full economic risk assessment.

3.1. Economic valuation of loss of life

A wide ranges of studies is available on the economic valuation of the statistical loss of life in various contexts, for example for road safety [6]. Here, the main approaches for the valuation of human life are discussed.

3.1.1. Costs of saving an extra life (CSX)
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 (I) is generally related to the reduction of the expected number of fatalities ($\Delta E(N)$):

$$CSX = I/\Delta E(N) \qquad (7)$$

It has been shown [12] how the cost of saving a human life per year (related tot 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 [5], showed that CSXY values vary widely across different sectors. This means that it not possible to determine a fixed amount that society is willing to invest to avoid the loss of one statistical life. Besides, for accidents with a low probability and large consequences the expected value of the loss of life will be small. The investments to prevent these types of accidents are generally considerable. Moreover, this type of cost effectiveness calculation of safety measures is risk neutral and does not reflect the social aversion against large-scale accidents (e.g. airplane crashes, large tunnel accidents). To overcome these burdens, there are other ways to validate the loss of a human life.

3.1.2. 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 [13]. In the case of individuals whose services are not marketed, a correction can be made. Further allowance is added for other costs related to accidents, such as medical costs, and police. In some countries a more or less arbitrary amount is added for the 'pain, grief and suffering' of the victim's relatives and friends. The major objection against this approach is that most people do not value their life for its economic output, but rather because it has intrinsic value to them. So this approach does not provide accurate measurement of

the parameter targeted. Instead it focuses on estimated production capacity.

3.1.3. Willingness to pay (WTP)

This approach is based on the trade off people make between risk and money [14,15]. How much are people willing to pay to reduce the risk of a premature death? It estimates the value that humans attach to life by means of surveys. These aim at the determination of 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 losses are added. The added components are only a small proportion of the total socio-economic costs of casualties. This approach usually yields higher values than the human capital approach.

3.1.4. Value of a 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. A study [16] gives an 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 of their income each, to save one expected statistical death among them. The Value of this Statistical Life thereby yields $5 million. 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.

Overall, there are several ways to valuate the prevention of the loss of life. When using the CSX method, the monetary value of a fatality has a wide range. However, the other methods (HCA, WTP, and VSL) all show an outcome in the same order, although their bases vary considerably. The methods described above can also be used to assign a monetary value to the prevention of injuries. Based on a study of road safety in the Netherlands [16], we estimate the values of the prevention of the loss of life and injury in this study at: $1.5 million/fatality and $0.2 million/injury (2002 price basis). It is noted that a recent overview of studies on the statistical value of life in road safety [6] give higher values, which are in the order of $4–5 million per fatality.

3.2. Including the indirect costs of tunnel accidents (traffic delay)

In addition to the direct costs (damage to the tunnel and its equipment, the vehicles and human suffering), there are also macro-economic costs. These costs are the indirect costs and comprise costs related to:

Table 2
Example of the time valuation of different users of a tunnel according to their motive [17,18]

Type of user	Time valuation (€/h)	Fraction of total traffic
Commuting traffic	6.5	0.5
Business traffic	23.0	0.25
Trucks	35.0	0.15
Other traffic	4.5	0.10

- 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 the traffic flow due to the collapse of a tunnel
- decreasing traffic volume (rerouting) caused by negative emotions due to recent tunnel accidents
- environmental damage

The indirect costs of traffic delay are calculated, based on [18]. The total associated economic losses are found by multiplying the time valuation of the traffic flow with the expected delays for all scenarios. It is clear that (the economic) appreciation of time varies between different users of a highway. Table 2 gives an example of the valuation of time according to the motive of the various users. It also shows the fraction of total traffic volume in the Netherlands that is formed by a certain type of user.

4. Towards an economic optimum for tunnel safety

4.1. Constraints with respect to the economic risk optimisation of Van Dantzig

To derive an economic optimum level for tunnels we need to be able to draw a figure like the one presented in Fig. 2. Thus, two relationships need to be investigated; the relation between investments and the achieved safety level, and the relation between the level of safety and the remaining economic damage. Section 3 presented a way of expressing the risk costs in financial terms. Presenting a clear relation between the investments and their quantified effect on the level of safety, however, appears to be difficult for a number of reasons.

First of all, as most studies on safety in tunnels are carried out from a deterministic point of view, the knowledge of the quantified effects of safety measures needed for a probabilistic approach is currently limited. Vrouwenvelder and Krom [6] show that economic optimisation can be carried out for a single measure in a tunnel. However, less is known about the cumulative effect of various safety measures and their
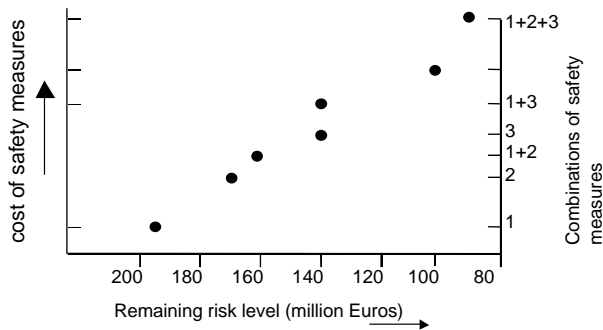
Fig. 3. Relationship between costs and effect of (combinations of) safety measures; a hypothetical case (see also [11] for a similar approach).

interdependence. The number of safety measures applicable to tunnels is considerable, with even more possible combinations. For a tunnel with M safety measures under consideration, the number of combinations (N) equals:

$$N_{combination} = \binom{M}{M} + \binom{M}{M-1} + \binom{M}{M-2} \cdots \binom{M}{1}$$

Thus, a tunnel with only 10 safety measures theoretically already yields more than 1000 combinations.

In order to establish a clear relation between the investments in safety and the achieved safety level, more research is needed to quantify the effect of safety measures, their interdependence, and their cumulative effects. With this knowledge, it could be possible to make an overview of all possible combinations of safety measures with their (cumulative) effect on the remaining risk and their costs. The required relation between investments in safety and their effect can then be drawn, clearing the way for an economic optimisation. Fig. 3 shows a simplified example of such a figure for a tunnel where only three safety measures are applicable. However, it should be noted that the function will not be 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 tunnel tube (1) or the installation of a sprinkler installation (2), or the construction of a shoulder (3).

4.2. A first step towards an economic safety optimum for tunnels

While the full economic optimisation of Van Danzig cannot be applied at this moment to tunnels as described above, a first step in the economic risk evaluation is made, by investigating the cost effectiveness of various safety measures individually. The investment costs related to tunnel safety are generally related to the:

- construction of the tunnel (e.g. uni- or bi-directional tube; construction of a shoulder, heat resistant lining)
- electrical installations (e.g. ventilation, cameras, speed detection systems)

- traffic management solutions (e.g. speed reductions, separating transport of dangerous goods)

Besides these costs, there are also maintenance costs and renovation costs. To compare all these investment costs and the risk cost over the economic lifespan of the tunnel, the Present Value method is used, taking into account the depreciation of money over time.

4.3. Graphic representation of the cost effectiveness of safety measures

There is insufficient knowledge on the cumulative effects of safety measures in tunnels. Thus, it is not yet possible to investigate the cost effectiveness of safety equipment, starting from an 'empty tunnel' and then adding safety equipment to the tunnel until it reaches an economic safety optimum. Therefore all safety measures are evaluated individually in relation to a reference point. When more knowledge on the quantified effect of safety measures becomes available, this approach may be used to investigate multiple reference points. Eventually this method can be used to investigate the combinations of and interactions between various safety measures and it will lead to an economic risk optimisation.

For this first investigation of the cost effectiveness of safety measures, one single reference point is used. As a reference point, it is assumed that the tunnel complies with the Personal and Societal risk criteria. Now, the cost effectiveness of various safety measures can be investigated by removing or adding safety measures.

The cost effectiveness relation can be represented in a figure showing the costs of safety measures versus the risk. Fig. 4 shows an example. The vertical axis shows the investments in safety. Above the horizontal axis the extra investments for additional safety measures are indicated, 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 and it is expressed solely in financial
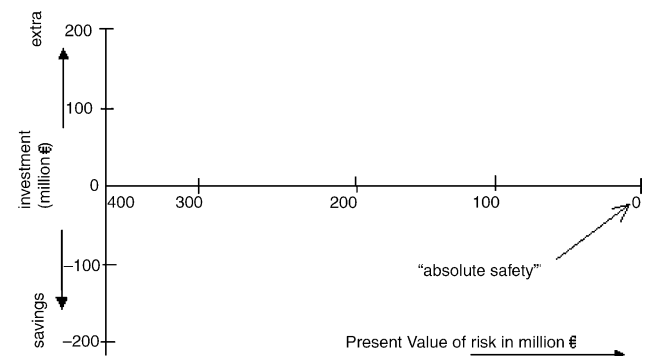

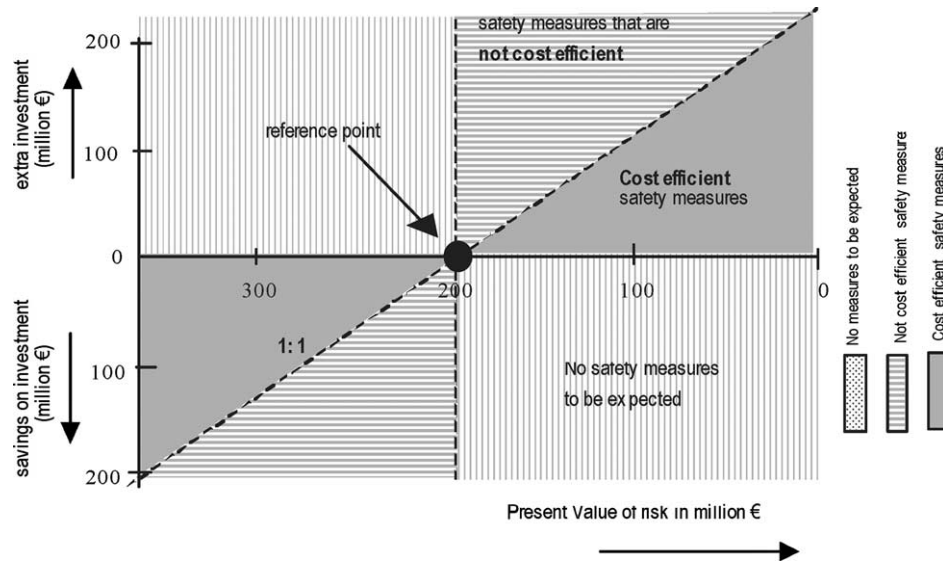Fig. 4. Investments in tunnel safety equipment versus risk.

Fig. 5. Graphic representation of cost effectiveness of safety measures.

terms. On the right hand side, the risk level 0 represents (the unachievable situation of) absolute safety.

Fig. 5 gives an example for an imaginary tunnel. The large dot in the middle corresponds with the reference point of the tunnel (e.g. the tunnel as designed), with a risk amount of €200 million over 30 years. The diagonal line through this point shows a one-on-one relation between investment costs and risk. All alternatives of adding or removing equipment can then be plotted in this figure. The two horizontal striped 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. Safety measures plotted in the two grey triangles are considered to be cost effective, because their costs/savings are lower than the reduction/increase in risk. The safety measures in the striped triangles are not cost effective, while their costs/savings are higher than their reduction/increase in risk.

4.3.1. Risk neutral or risk averse

The cost effectiveness relation in Fig. 5 can be used to evaluate the cost effectiveness of safety measures in various ways. When both axes are presented as the Expected Values, the figure gives a risk neutral relation between the investments in safety (vertical axis) and the present value of risk (horizontal axis). However, it is also possible to use other values on both axis to take into account the uncertainties in investments, or the social aversion towards large-scale accidents. In both cases, for instance it is possible to use the Characteristic Value ($CV = E(N) + k\sigma(N)$, see also Section 2), instead of the Expected Value, which makes the relation risk or cost averse. The risk aversion will mainly apply to accidents with smaller probability and larger consequences, i.e. especially those with multiple injuries and fatalities. Although risk aversion is generally only applied to loss of human life, it can be

discussed whether risk aversion would be appropriate for large economic consequences. For example, consider two bets with equal expected losses. In the case of risk aversion, a very large loss with a small probability (e.g. €100.000 with probability 10^{-5}) could be valued worse than a smaller loss with a larger probability (e.g. €100 with probability 10^{-2}).

4.4. Relation to the risk optimisation of Van Dantzig

The analysis presented above uses a certain tunnel design as a reference point in order to investigate the cost effectiveness of safety measures. This means that the effectiveness of safety measures depends heavily on the safety level of the reference point taken. Following the general economic law of diminishing returns, it can be expected that investments in safety will be more effective in a tunnel without equipment than in a fully equipped tunnel. However, if this calculation is made using several different reference points, the relation needed for an economic optimisation can be found. This is presented in Fig. 6 below, which shows several reference points and
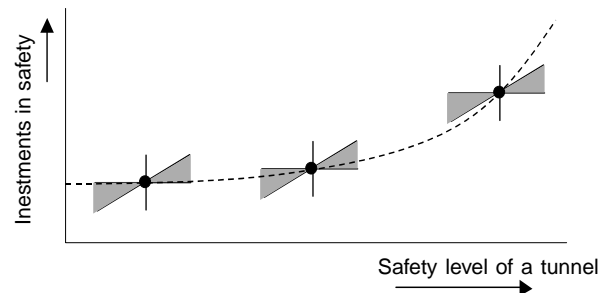

Fig. 6. The proposed risk evaluation method in relation to the curve of Van Danzig.

the cost effectiveness of safety measures according to these safety levels. Note that in the original application by van Danzig for flood protection considered one measure (dike heightening) and a linear relation between investments and safety level.

The dotted line in the figure shows a rough estimation of the relationship between the investments in safety and their effect. Added to this figure are three black dots representing three different reference points, with three different levels of safety equipment. The triangles represent the areas where safety measures are considered cost effective, where $\Delta(\text{Investment})/\Delta(\text{Safety}) \leq 1$.

5. Case studies: risk standards and evaluation of safety measures in Dutch tunnels

This section illustrates the application of the three risk criteria as presented in Section 2 and the analysis of cost effectiveness as discussed in Section 4, using several cases of safety analyses of Dutch tunnels.

5.1. Individual and group risk

The Individual- and Group Risk criteria are commonly used to evaluate the risk of 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 below, in Table 3.

The personally acceptable risk can be presented as the probability of death per kilometres travelled per year or the probability of losing life for an average user or employee. The actual risk of death for road users in the Netherlands is the order of 10^{-8} per person kilometre per year. For the Western Scheldt tunnel more strict standards for individual risk are chosen as the decision makers wanted the anticipate growth of traffic and the potential of accidents with large consequences. In addition they desired that the (new) tunnel should add a marginal level of risk to its users. For the judgment of societal risks both FN limits and limits for the characteristic value (with $k=3$) 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 [20].

5.2. Economic risk evaluation

The evaluation of cost effectiveness as outlined in Section 4 was used to investigate the cost effectiveness of several safety measures in three tunnels in the Netherlands (bored, land and immersed) [21]. The tunnels were all in the design or construction phase at the time of investigation. The risk reducing effects of various safety measures were analysed with a quantitative risk analysis model for the evaluation of the internal risk [22]. The costs of the safety measures were provided by several departments of the Ministry of Transport. The results for the land tunnel are presented below. The tunnel has a length of approximately 2.5 km, it has two traffic lanes (and shoulders), the expected daily traffic volume in 2020 is estimated at 48,500 vehicles, and there are no restrictions on the carriage of hazardous cargo.

5.2.1. Risk neutral approach (using the Expected Value of economic damage)

Fig. 7 shows the cost effectiveness of the safety measures under consideration for this tunnel in relation to the Expected Value of risk. It is clear from the figure that removal of the following measures seems cost effective in relation to the EV of risk: removing the (hard) shoulder (3) and removing the fire extinguishing facilities (7) seems cost effective regarding the EV of risk. Removing the ventilation equipment is almost cost efficient, while removing half the number of emergency exits (4), does not save a lot of money and does not influence the level of safety considerably.

Regarding the additional safety measures, it can be seen that separating the 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) does not cost much for this land tunnel, but has a limited influence. Other additional safety measures such as improving the use of fire extinguishing tools (13) and escape routes (14) are cost effective. Even 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 enforcing a speed reduction in the tunnel (12).

5.2.2. Risk averse approach (using the Characteristic Value of economic damage)

In order to take into account the social aversion towards large-scale accidents, the evaluation of the cost

Table 3
Overview of safety standards applied to three Dutch tunnels [19,20] (for the CV, $k=3$)

		Tunnel		
		High speed train link	Western Scheldt tunnel	Betuwe tunnel
Individual risk	users/pass.	1.5×10^{-10}/km/yr	1×10^{-10}/km/yr	Betuwe tunnel
	Employees	5×10^{-5}/yr	—	5×10^{-5}/yr
Group risk	F_N	$4 \times 10^{-2}/N^2$/yr/km	$10^{-2}\ N^2$/yr/km	$10^{-2}\ N^2$/yr/km
	Charac. value	2,3 fat/yr	—	—

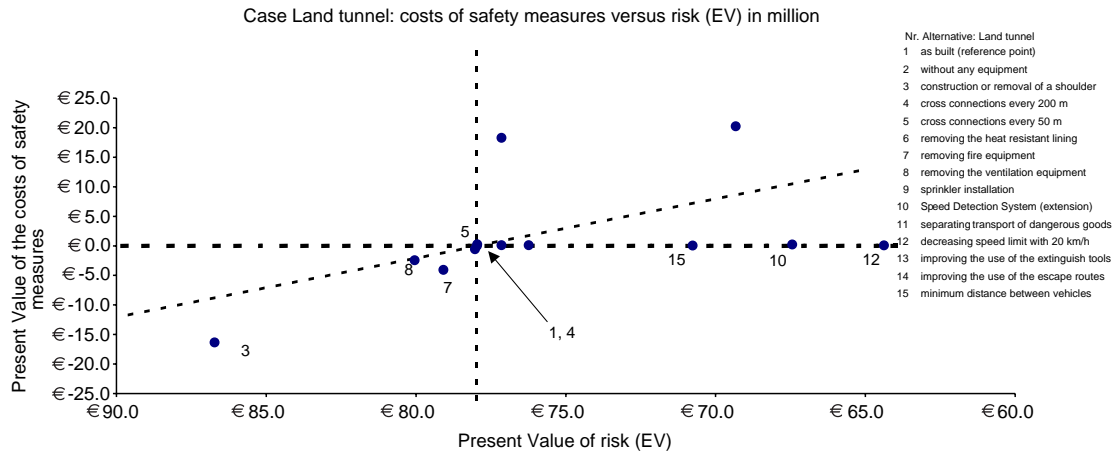Case Land tunnel: costs of safety measures versus risk (EV) in million

Fig. 7. Costs of safety measures in relation to the expected value of risk in million Euros.

effectiveness of safety measures was also done in relation to the Characteristic Value of risk (with $k=3$). The graphic results are presented in Fig. 8.

It is clear that the horizontal axis is stretched out relatively. As a result some safety measures are cost effective in a risk averse approach, while they are not cost effective in a risk neutral approach (safety measures 3, 7, 8 and 11). The only safety measure that is still not cost effective, even in a risk averse approach, is the installation of a sprinkler system (nr. 9). All other safety measures that can be added to the design are cost effective in a risk-averse approach. Considering the removal of safety measures, it can be seen that removing any of the safety equipment from the design is not cost effective in a risk averse calculation.

5.2.3. Discussion of results

The same analysis was carried out for two other tunnels (a bored, and an immersed tunnel). All evaluations using the expected value showed that the casualties of normal accidents account for about 90% of all casualties. In a risk-averse approach, one could argue that tunnel specific fatalities would deserve larger expenditures and that the risk neutral approach is less suitable. Societal risk aversion will mainly apply to accidents with smaller probability and larger consequences, i.e. especially those with multiple injuries and fatalities. Thus the weight of these injuries and fatalities will increase relative to the risk neutral calculation. Although more discussion on the appropriateness of the concept risk aversion is needed, it is noted that the current standards for tunnel safety in the Netherlands (see Table 3) set by the decision makers clearly reflect this risk aversion.

The safety measures that aim specifically at reducing the risks of 'small probability large consequences'—accidents (e.g. a sprinkler system or doubling the distance of the cross connections), are not cost effective even in a risk averse evaluation. The best option is to separate trucks carrying dangerous cargo from the rest of the traffic. It is not cost effective in relation to the Expected

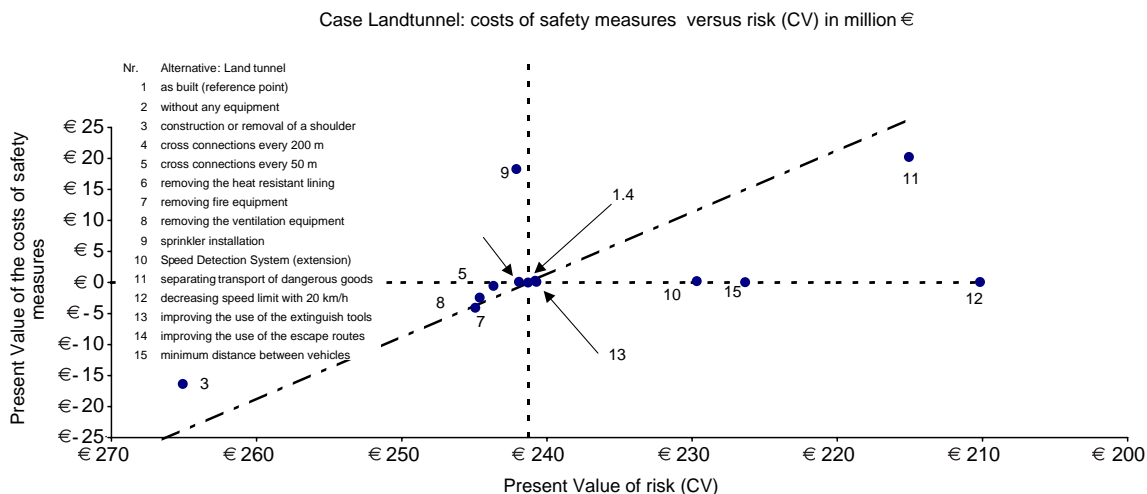Case Landtunnel: costs of safety measures versus risk (CV) in million €

Fig. 8. Costs of safety measures in relation to the Characteristic Value of risk in million Euros.

Table 4

Example of a cost effectiveness analysis of a shoulder, including costs of traffic delay. Expected values of economic damage for different damage categories (vertical axis) and different design alternatives (horizontal axis)

Case: land tunnel	2 lanes WITH shoulder	2 lanes WITHOUT shoulder	2 lines WITH/3 WITHOUT shoulder
Casualties			
Accidents			
Injured	€2.197.000	€3.042.000	€2.682.000
Fatalities	€2.944.000	€4.076.000	€3.594.00
Calamities			
Injured	–	–	–
Fatalities	–	–	–
Material damage			
Accidents			
Material damage to the vehicles material damage to the tunnel	€1.429.00	€1.726.000	€1.599.000
Calamities			
Material damage to the vehicles material damage to the tunnel	€7.010	€7.650	€7.650
	€115.000	€125.500	€125.500
Congestion			
Breakdown accidents	€0	€978.000	€23.000
Accidents	€5.770.000	€9.721.000	€1.086.000
Calamities	€89.500	€107.400	€99.800
Maintenance	€0	€0	€0
Total without investments	€12.611.000	€19.859.000	€9.285.000
Difference	€0	€7.248.000	€3.326.000
Maintenance (30 years)	€21.319.000	€19.187.000	€21.333.000
Investments	€132.210.000	€118.989.000	€132.298.000
Net present value (30 years)	€166.140.000	€158.035.000	€162.916.000
Difference	€0	€8.105.000	€3.224.000

Value of risk, though it is when the Characteristic Value is taken into account. Though, the most (cost) effective measures are the ones that prevent the accidents from happening, or reduce the effect in the early stages of the development of the accidents. Examples are: the introduction of a minimum distance between vehicles and improving the use of fire extinguishing facilities and escape routes, and above all enforcing speed reductions in the tunnels.

Of the safety measures where removal was considered, removing the fire resistant lining or the ventilation equipment is not cost effective. Surprisingly, evaluation of the removal of the fire extinguishing equipment from the tunnels *as built* seems to be cost effective (and the tunnel still complies with the social risk criterion).

From the three cases studied, it can be concluded that the safety level of a tunnel mainly depends on the length of the tunnel, the daily traffic volume and the number of trucks transporting dangerous goods.

Finally, the height of the monetary values assigned to casualties was investigated. Its value has little influence on the evaluation of cost effectiveness of the safety measures. This is due to the fact that the cost effectiveness in this investigation is regarded in relation to the tunnel as built. Therefore, changing the monetary values will also change the reference point of the investigation. A higher value for

a statistical life will therefore only stretch the horizontal axis to a limited extent.

5.3. Including traffic delay as a result of accidents

The above analysis showed that removing the shoulders from the tunnel is not cost effective in a risk neutral approach. It is interesting to investigate its cost effectiveness when the indirect costs of traffic delays as a result of tunnel accidents are also taken into account. These calculations were made using the BOMVIT model [17].

The reference situation with a shoulder was compared with two alternatives: a design without a shoulder and a tunnel with a shoulder that is turned into a traffic lane halfway its economic lifespan. A summary of the results of the analysis including direct and indirect risk is presented in Table 4. It shows that two alternatives 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 present value of the project (with €3.2 million[2]) when it is compared with the reference situation. Even more profitable is removing the shoulder in

---

[2] All these Present Values are calculated using total cost including taxes and are expressed in €s with the base year 2002.

the Land tunnel. It will reduce the total investment with €15.4 million (PV), but 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.

6. Conclusions

It is the aim of this paper to propose a framework for the evaluation of tunnel safety. A probabilistic framework has been proposed for the judgment of personal, societal and economic risks of tunnels. The most stringent of the three should be adopted as basis for the 'technical' advice to the political decision makers.

Because the knowledge on the quantified (cumulative) effects of safety measures applicable to tunnels needed for an economic risk optimisation is limited at the moment, it is not (yet) possible to adapt the economic risk optimisation method of Van Dantzig to determine an economic safety optimum for tunnels. However, a first step towards an economic risk evaluation is presented, that includes both material and immaterial costs resulting from accidents. Moreover, a way to include the costs of traffic delay in the evaluation is suggested.

An analysis of the application of elements of the proposed framework in practical situations has shown that standards for limitation of personally and social acceptable risk are commonly applied in tunnelling projects in the Netherlands. However, there is less experience with the economic assessment of safety measures. Application of the economic evaluation method proposed in this paper gives promising results. Surprisingly, it shows that some of the safety measures (e.g. fire extinguishers), commonly applied in tunnels at the moment, are not cost effective from a probabilistic point of view. But it also underlines the relevance of some of the safety measures generally applied on tunnels (ventilation and fire resistant lining). The cost effectiveness analysis showed that preventive measures are most cost effective. These results can be used during the design of other tunnels.

The current risk standards applied in the Netherlands and the investments in tunnels clearly reflect risk averse preferences of decision makers. Further discussion is encouraged on appropriateness of risk aversion with regard to 'small probability—large consequence' accidents.

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 rational and effective decision making with regard to the investments in tunnel safety.

7. Disclaimer

Any opinions expressed in this paper are those of the authors and do not necessarily reflect the position of the Dutch Ministry of Transport, Public Works and Water Management.

References

[1] Geyer TAW, Morris MI. Channel tunnel safety case: quantitative risk assessment methodology. Proceedings of the 1996 annual meeting of the society for risk analysis Europe 1996.

[2] Eisner HS. The channel tunnel safety authority. Saf Sci 2000;36(1): 1–18.

[3] Mashimo H. State of the road tunnel safety technology in Japan. Tunnelling Underground Space Technol 2002;17(2):145–52.

[4] Diamantidis D, Zuccarelli F, Westhauser A. Safety of long railway tunnels. Reliab Eng Syst Saf 2000;67:135–45.

[5] Tengs TO, Adams ME, Pliskin JS, Gelb Safran D, Siegel JE, Weinstein MC, et al. Five-hundred live saving interventions and their cost effectiveness. Risk Anal 1995;15(3):369.

[6] Dionne G, Lanoie P. Public choice about the value of a statistical life for cost benefit analysis—the case of road safety. J Transport Econ Policy 2004;38(2):247–2747.

[7] Vrouwenvelder ACWM, Krom AHM. Hazards and the consequences for tunnel structures and human life. Proceedings safe and reliable tunnels. Innovative European achievements, Prague 4–6 February 2004 p. 23–32.

[8] Vrijling JK, Hengel W, van Houben RJ. Acceptable risk as a basis for design. Reliab Eng Syst Saf 1998;59:141–50.

[9] Vrijling JK, Hengel W, van Houben RJ. Framework for risk evaluation. J Hazard Mater 1995;43:245–61.

[10] van Dantzig D. Economic decision problems for flood prevention. Econometrica 1956;24:276–87.

[11] Bohnenblust H. Risk-based decision making in the transportation sector. In: Jorissen RE, Stallen PJM, editors. Quantified societal risk and policy making. New York: Kluwer Academic Publishers; 1998.

[12] Vrijling JK, van Gelder PHAJM. In: Cottam MP, Harvey DW, Pape RP, Tait J, editors. An analysis of the valuation of a human life. ESREL 2000—Foresight and precaution, Edinburgh, Scotland, UK, vol. 1, 2000. p. 197–200.

[13] ICF, Consulting Ltd. Costs and Benefits of Rehabilitating Road Tunnels in View to Enhance Safety, DRAFT Phase I Report: EU Tunnels, 26 April; 2002.

[14] Van Gelder PHAJM. Cost benefit analysis of drugs against AIDS in South Africa using concepts of Willingness-to-Pay, Value of a statistical life, evidence based medicine and life-quality index; some on-going results, Chapter 2 of the Annual Report 2002, SANPAD project New Models in Survival Analysis, Editors: van Gelder PHAJM, de Waal DJ, Workshop on advanced models in survival analysis, Bloemfontein, January 13; 2003. http://www.waterbouw.tudelft.nl/public/gelder/sanpadannualreport2002.pdf

[15] Hammit JK. Valuing lifesaving: is contingent valuation useful? Published Risk Perspect 2000;8(3):2000.

[16] Wesemann P. Kosten van de verkeersonveiligheid in Nederland in 1997. Leidschendam: Stichting Wetenschappelijk Onderzoek Verkeersveiligheid; 2000.

[17] Broeren PTW. BOMVIT Beslissings Ondersteunend model. Vluchtstroken In tunnels, Case: Leidsche Rijn, Concept 23-10-2002; 2003.

[18] V&W. Eindrapportage Veiligheid Westerscheldetunnel, WSRD-970568, 18 April 1997, Ministerie van Verkeer en Waterstaat, Ministerie van Binnenlandse Zaken en KMW; 1997

[19] Molag M. Overzicht normen spoor (an overview of risk limits for railway tunnels), TNO MEP documents; 2002.

[20] Tweede Kamer. Risiconormering gevaarlijke stoffen, vergaderjaar 1995–1996, 24 611nr. 2; 1996.

[21] Arends BJ. Value of safety, evaluation of the cost effectiveness of safety measures in road tunnels in the Netherlands. Master Thesis, Delft University of Technology, Faculty of Civil Engineering, Department of Hydraulics; 2003. http://www.waterbouw.tudelft.nl/education/MScTheses/2003/2003Arends.pdf

[22] Weger D, de Kruiskamp MM, Hoeksma J. Road tunnel risk assessment in the Netherlands, TUNprim: a spreadsheet model for the calculation of the risks in road tunnels. In: Zio E, Demichela M, Piccinni N, editors. ESREL 2001, International Conference, Torino, Italy September 16–20.