TNO Publication
TNO-MEP – P 96/006

TNO decision model for the transport of hazardous materials through road tunnels

TNO Institute of Environmental Sciences, Energy Research and Process Innovation

Laan van Westenenk 501
P.O. Box 342
NL-7300 AH Apeldoorn
The Netherlands

Phone +31 55 549 34 93
Fax +31 55 541 98 37

author:
F.J. Verheij
M. Molag

date:
February 1996

order no.:
27186

keywords:
– decision modelling
– quantitative risk analysis
– transport of hazardous materials

sponsor:
To be presented at the OECD seminar on:
Transport of Dangerous Goods through Road Tunnels
Risk Assessment and Decision Making Process: Methodologies, Models, Tools
11th-13th March 1996, Oslo, Norway

TNO DECISION MODEL FOR THE TRANSPORT OF HAZARDOUS MATERIALS THROUGH ROAD TUNNELS

F.J. Verheij and M. Molag
TNO Institute of Environmental Sciences, Energy Research and Process Innovation
P.O. Box 342
7300 AH Apeldoorn
The Netherlands

Abstract

Although transport of hazardous materials is supposed to be safe [CTGG, 1992] it still is associated with risks. The transport of hazardous materials requires therefore specific attention in order to meet safety standards. One important aspect involves risks to the public.
The application of tunnels for transport purposes is being considered in various cases. The risks for road users on the tunnel route, however, will increase and the possibility of irreparable damage to the tunnel exists. On the other hand transport of hazardous materials via diversions will increase the risks to the public, as diversions usually are closer to residential areas than are highways with tunnels.
Here a decision problem arises. The key question is: *which route is, for a specific location, preferable for transporting hazardous materials, or certain classes of them, and is the transport of these materials acceptable in terms of risk?* In order to support policy and decision makers in finding the 'best' answer TNO has developed a decision model. Quantitative risk analysis is used to calculate the risks involved. The outcome of these calculations define the category of the decision problem.
The present TNO decision model has demonstrated to be a powerful tool for decision-making processes on transport of hazardous materials through road tunnels. It already has been applied to several road tunnels in The Netherlands.

1. Introduction

The increasing density of population in combination with the strongly increasing intensity of road traffic makes decisions concerning land use and regional planning of increasing complexity. This holds for the Netherlands as well as for a lot of other places all over the world. To solve the transportation problems numerous road tunnel projects are developed and carried into effect.
However, another decision problem arises, i.e. the transport of hazardous materials through tunnels. Accidents with loss of containment of hazardous materials can occur during transport of these materials. The consequences of such accidents can be the release of a toxic or a flammable material. The release of a toxic material can

cause intoxication, the release of a flammable material can result in a BLEVE, flash-fire, explosion or pool fire. Due to these effects victims amongs traffic participants and people living in the vicinity of the road are possible. Besides, a tunnel could be destroyed. Before allowing the transport of hazardous materials through a specific tunnel the decision maker has to decide if the risks of these shipments are acceptable. At least the following conditions have to be met:

- the probability of irreparable tunnel damage as a result of fire or explosion must be small;
- measures should be taken to prevent tunnel damage, e.g. applying heat-resistant wall coating, installing water seals, making the pump chambers explosion-proof and ensuring that the capacity of the drainage system is sufficient;
- measures should be taken to prepare for emergency situations, e.g. providing the tunnel with sufficient fire protection as well as fire fighting systems, communication facilities and a safe escape route;
- governmental agreement must be reached concerning the authorization of the transport of hazardous materials.

In the eigthies TNO developed a decision model to aid decision-making on the road tunnel transport of hazardous materials [Jansen & Janssen, 1982], [Van Steen, 1987]. The starting point for the decision model is the following key question: *which route is, for a specific location, preferable for transporting hazardous materials, or certain classes of them, and is the transport of these materials acceptable in terms of risk?* The basic principle of the TNO decision model is that the risks concerning the transport of hazardous materials through a tunnel are compared with the risks of the transport via a diversion in a quantitative way.
Risk analysis provides insight into the risks associated with the transport of hazardous materials, where risk refers to the possibility of undesirable consequences such as fatalities or economical costs.

In the Netherlands the regulations concerning the transport of hazardous materials distinguish two categories of road tunnels. A tunnel is marked 'category II' if no special safety requirements are fulfilled except heat-resistant coatings. Only the transport of a few selected categories of hazardous materials are allowed to transport through such tunnels. A tunnel is marked 'category I' if the transport of flammable liquids with a flash point lower than 21°C (e.g. petrol) through this tunnel is allowed. A number of safety requirements then has to be fulfilled. If the transport of other hazardous materials is allowed too a road tunnel is neither marked 'category I' nor 'category II'. Apart from this distinction between tunnels sufficient measures are taken in all tunnels to keep the risks as low as reasonably acceptable (the ALARA principle).
The TNO decision model has been developed such that an answer is given about the size of the risks of each route and that insight is provided in the outcome of each route on both aspects, i.e. fatalities and economic costs. It enables the decision maker to check wether a specific tunnel route meets the safety requirements as well as to com-

pare the alternatives.
Of course the methodology can also be applied to support the choice between various designs of a specific tunnel route [e.g. Jansen, 1995 Westerschelde].

This paper discusses the decision model developed. Section 2 describes the model, in terms of the steps that are distinguished, and some methodological considerations. The application to a specific decision problem is described in section 3. The paper concludes with a discussion about new developments and thoughts in section 4.

2. Model description

The purpose of the TNO decision model is to find an answer to the aforementioned key question, viz. ***which route is preferable for transporting hazardous materials and are these transports acceptable in terms of risk?*** The following requirements had to be met in view of the ultimate application of the decision methodology to each of the Dutch tunnel locations:
- the possible consequences of so-called undesirable events, which may occur during road transport of hazardous materials, must be estimated quantitatively;
- insight has to be provided into the value judgments that might be necessary to make a choice between the different routes;
- the necessary computing has to be performed by means of a desk calculator (this requirement was formulated in the eighties!).

Decision modelling techniques provide a framework for answering the key question. The main information is provided via quantitative risk analysis methods. Risk reduction measures, both technical (e.g. materials, safety systems) and organisational (e.g. communication, co-ordination), can influence the result of the risk analyses and, thus, might affect the decision to be taken.

The decision model developed consists of a number of consecutive activities. Figure 1 presents a schematic representation of the model structure. This section describes the activities to be performed in order to answer the key question. Four principal steps are distinguished:
1. Characterize the alternatives; one of the activities here is investigating maps of the routes and their environment.
2. Specify the relevant aspects and employ a calculation scheme that leads to the result of the quantitative risk analysis calculations.
3. Analyse the decision problem on the basis of this result; relevant activities here are determining the category to which the decision problem belongs, employing value relationships and calculating the respective components of the aforementioned result.
4. Perform a sensitivity analysis that might lead to one of several supplemental steps.

An extensive description of these steps is to be found in [Jansen & Janssen, 1982], [Van Steen, 1987] and [Jansen, 1990]. A brief summary is written in this section.

2.1 Characterize the alternatives

Each route has its specific risks. In order to characterize the alternatives data have to be collected and maps of the routes and their environment have to be investigated. Characterizing the alternatives involves the following activities:

Determine road types
Statistics on road accidents in terms of fatalities and damage on the road itself show differences between the various road types. Distinctions has been made between one-lane and dual lane roads, between motorways and secundary roads as well as between roads within town areas and roads outside town areas. The frequency of occurrence of road accidents in tunnels have been derived from casuistry and data on traffic intensity.

Divide routes into road sections
The roads have to be divided into sections of at least 500 m length. The division has to be made such that a homogeneous distribution of the density of population is reached up to a distance of 100 m from the road and in the area between 100 and 250 m from the road.

Determine population and value categories
In order to enable calculations of the consequences of a road accident for the surroundings the density of the population as well as the density of the economic value (recovery costs) of houses, buildings etcetera has to be defined. Both for the population and for the economic values four density categories are distinguished.

Characterize constructions, e.g. the tunnel
The potential damage due to road accidents in the tunnel depends on length, value of the tunnel (repair costs), number of tubes, number of lanes per tube and type of ventilation amongs others.

Determine hazardous materials distribution across shipments
The distribution of different types of hazardous material across shipments is determined by calculating the fractions of vehicles carrying the various categories of hazardous materials. Five categories are distinguished: explosives, flammable gases, flammable liquids, toxic liquids and toxic gases. A standardized distribution is used within the calculation model. Specific data on the actual distribution, however, may be useful.

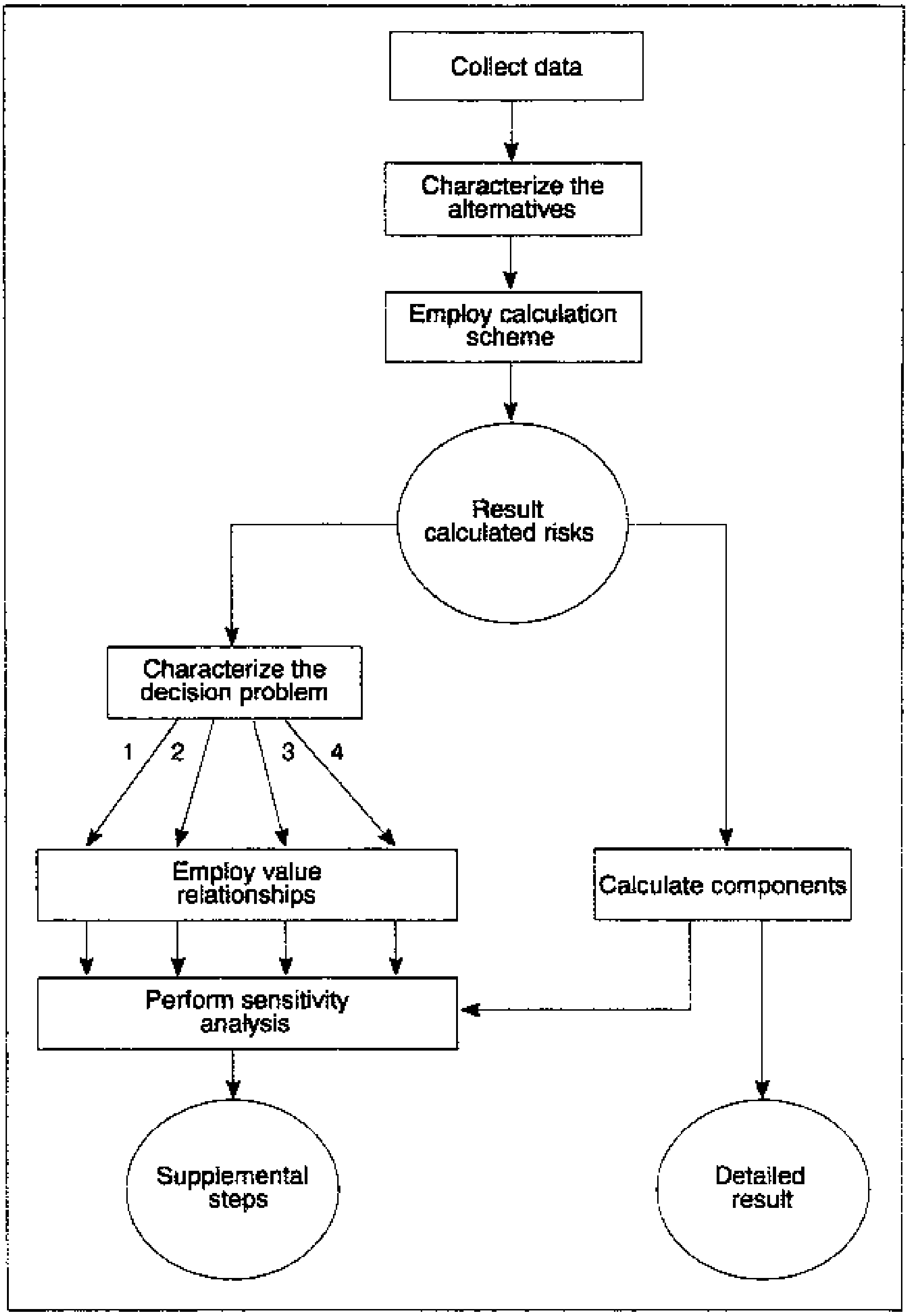

Figure 1 *Schematic representation of the TNO decision model.*

2.2 Employ calculation scheme

Accidents influence our ideas of risks. The size of a potential accident, controllability and benefit-related aspects has been identified to be essential factors in *risk perception* [Covello, 1983]. The apparent importance of the first of these factors is consistent with the existence of a phenomenon called *risk aversion*, i.e. usually a larger weight is assigned to large accidents or losses in comparison with small ones. From research it appears that people tend to consider risky activities as a whole, and to weigh benefits against disadvantages implicitly or explicitly. This makes decision analysis an appropriate approach for dealing with acceptable risk problems.
Decision analysis is a discipline that deals explicitly with uncertainty and with value judgments like trade-offs and risk aversion [Keeney & Raiffa, 1976]. Adopting this approach for acceptable risk problems is equivalent to recognizing that these problems essentially involve a decision among alternatives which are characterised by a number of aspects, of which risk is just one. It is possible, therefore, to incorporate in a natural way an aspect that happened to be one of the major motives for the key question, viz. economic costs.
Environmental aspects, e.g. air and noise pollution, are of increasing importancy and, thus, could also be considered as a major criterion. This point is discussed in section 4. In the present TNO decision model, however, the aspects considered are fatalities and economic costs.

The results of the previous stage serve as input to the calculation scheme. Additional information on damage factors and on probability functions/tables/schemes of fatalities and economic costs is required for the quantitative risk analysis. The following attributes contribute to these two aspects.

- Fatalities:
  - fatalities on the road/in the tunnel, due to traffic accidents with release of hazardous materials;
  - fatalities in the environment, due to traffic accidents with release of hazardous materials;
  - fatalities, due to traffic accidents without release of hazardous materials.
- Economic costs:
  - material damage, due to traffic accidents which are followed by or due to hazardous materials release;
  - material damage, due to traffic accidents without release occurring;
  - additional transportation costs, associated with the longest of the two routes;
  - damage due to transportation;
  - economic losses, caused by irreparable tunnel damage.

The calculation model used for calculating probability distributions of fatalities and economic costs consists of a damage model and a probability model.

The *damage model* calculates number of fatalities and size of economic costs depending upon four variables: accident location, substance, accident scenario and type of damage. The last variable relates to the possibility of different types of dam-

age within one accident scenario.
For a number of typical road types as well as for different tunnel types consequences due to fire and explosion, resulting from ignited release of a flammable liquid, have been calculated for three release scenarios. The selection of these accident scenarios is based on case histories of accidents in which flammable liquids have been involved (source: TNO accident data base FACTS, [FACTS]).

The *probability model* calculates the frequency of occurrence of several types of accidents and the probabilities associated with the possible damages. The combination of consequences and probabilities result in so-called damage factors Ev_j. These damage factors have to be derived on an expected value basis for each combination j of road type and environment category, as well as for the tunnel. A damage factor is the product of:

- the fraction of the shipments carrying a specific category of hazardous materials,
- the probability of the consequences to occur,
- the size/the area of the damage,
- the percentage of fatalities among the exposed persons or the percentage of the material damage as part of the economic value,
- the percentage of the concerning persons who will be exposed to the effect,
- the density of population or the density of the value of houses etcetera.

Damage factors have been calculated for a number of relevant combinations. The damage factors are divided into factors for fatalities and factors for material damage (economic costs). In addition, damage factors were calculated which separate out the contribution of large accidents to all undesirable events. In this way the effect of the abovementioned risk aversion can be taken into account in the decision-making process.

The result of the quantitative risk analysis calculations consists of expected values for fatalities and economic costs for each route. The *total expected value* (EV) is defined as the product of the frequency of occurrence of the defined accidents, the damage factor (EV-factor) and the length of the route. The expected values concerning accidents resulting in 20 fatalities or more or in economic costs above $10 x 10^6$ Dfl contribute to the *expected value due to large accidents* (ELA). Expressed in formulae:

$$EV = \Sigma_j (f_j \, x \, EV_j \, x \, L_j) + C \, x \, \Sigma_j L_j \qquad (1)$$

$$ELA = \Sigma_j (f_j \, x \, ELA_j \, x \, L_j) \qquad (2)$$

where

- EV is the total expected value for the route;
- ELA is the expected value of large accidents for the route;
- f_j is the frequency of occurrence of the defined accidents;
- Ev_j is the damage factor for combination j of road type and environment category;

- ELA_j is the damage factor of large accidents for combination j of road type and environment category;
- C is a factor to calculate the transport costs (average costs per km times length of the route);
- L_j total length of type j road section.

The result of the quantitative risk analysis calculations is conveniently arranged in tables, see figure 2. This table is to be applied to both fatalities (subscript f) and economic costs (or material damage, subscript m).

	Tunnel	Diversion	Alternative 3 .... alternative x
EV_f	1.50	3.20	...
ELA_f	0.09	0.13	...

	Tunnel	Diversion	Alternative 3 .... alternative x
EV_m	100	50	...
ELA_m	5	0	...

Figure 2 *Presentation of the result of the calculation of the expected values, concerning fatalities (expressed in 10^{-7}/shipment, upper figure) and concerning economic costs (expressed in 10^{3} Dfl/shipment, lower figure).*

Most often the number of alternative routes is restricted to 2. Extension, however, is possible but complicates the decision problem. In the further discussion we follow the restricted number of alternatives.

2.3 Analyse the decision problem

On the basis of the result of step 2, a preliminary decision may be made. However, this decision may not prove to be a robust one over all situations. Moreover, situations may occur, in which even a preliminary decision is not obvious based purely on the outcome of the calculated risks. This could occur when:

- the differences between the alternatives are small;
- large accidents require that risk aversion is taken into account;
- a trade-off between fatalities and economic costs is required.

In these situations further analysis of the decision problem is necessary, taking the result of step 2 as starting point. Characterizing the decision problem is performed by determining the category to which it belongs. The classification of categories is based on whether value judgments are necessary or not, and, if so, on whether the required value judgments are related to trade-off, to risk aversion or to both. Considering all possible patterns, four principal categories exist (the aterisks in the figures below denote the preference):

Category 1. All four numbers, EV_f, EV_m, ELA_f, ELA_m, of one alternative are smaller than these numbers of the other alternative. In the figure below alternative 1 is clearly preferred and no value judgments are necessary. Further analysis is limited to checking robustness of the result.

	Alternative 1	Alternative 2
EV_f	*	
ELA_f	*	

	Alternative 1	Alternative 2
EV_m	*	
ELA_m	*	

Category 2. The expected values, both EV and ELA, belonging to fatalities are smaller in one of the alternatives and these values belonging to economic costs are smaller in the other alternative. In this case the choice depends upon the trade-off between fatalities and economic costs. An example is shown in the figure below.

	Alternative 1	Alternative 2
EV_f	*	
ELA_f	*	

	Alternative 1	Alternative 2
EV_m		*
ELA_m		*

Category 3. Here risk aversion is relevant. This category shows different preferences for total expected values and large accident expected values for both aspects; fatalities and economic costs. In this case the choice depends upon the degree of risk aversion, see also figure below.

	Alternative 1	Alternative 2
EV_f		*
ELA_f	*	

	Alternative 1	Alternative 2
EV_m		*
ELA_m	*	

Category 4. Within category 4 risk aversion and the trade-off between fatalities and material and economic costs must in principle be considered together. However, in a number of situations simplification is possible by separation of these two value judgments (category 4A: separable problems, an example shown in the first figure below). For the non-separable problems (category 4B, an example shown in the second figure below) application of weighing factors is recommended, see also section 4.

	Alternative 1	Alternative 2
EV_f		*
ELA_f	*	

	Alternative 1	Alternative 2
EV_m		*
ELA_m		*

	Alternative 1	Alternative 2
EV_f		*
ELA_f	*	

	Alternative 1	Alternative 2
EV_m	*	
ELA_m		*

It appeared that category dependent simplifications are possible, leading to convenient value relationships in terms of break-even points and preference conditions. To employ these value relationships first requires a calculation of differences between absolute values. The notation is as follows:

$$ev_f = EV_{f,1} - EV_{f,2} \qquad (3)$$

where
EV_f is the total expected value of fatalities,
subscript 1 refers to alternative 1 and subscript 2 refers to alternative 2.

Filling in the numbers given in the example of figure 2 into equation 3 the result would be:

$$ev_f = 1.5 - 3.2 = -1.7 \times 10^{-7} \textit{ fatalities/shipment}$$

Similar formulae apply to the other characteristic numbers. Thus four difference values are calculated.

The respective value relationships were derived from several formulae, which represent differences between alternatives from various perspectives. It is possible to take into account the impact of risk aversion. This is done by introducing a *risk aversion* factor u, which weights the contribution of large accidents ($u > 1$). In addition, joint treatment of the two attributes 'fatalities' and 'economic costs (material damage)' is effected by introducing a *trade-off* factor b, which is equivalent to the amount of the economic costs one is willing to accept in order to prevent one fatality. In (2) both risk aversion and trade-off are considered in the difference D between the alternatives:

$$D = b\,[ev_f + (u - 1)\ ela_f] + [ev_m + (u - 1)\ ela_m] \qquad (4)$$

Break-even points at which the preference switches from one alternative to the other can be calculated with this formula for all four categories. An extensive description can be found in [Van Steen, 1987] and [Jansen, 1990].

Using the numbers given in figure 2 the decision problem is marked category 2. Filling these numbers the difference D (per shipment) between the tunnel route and the diversion would be:

$$D = b\,[-1.7 - (u - 1)\ 0.04] \times 10^{-7} \textit{ fatalities} + [50 + (u - 1)\ 5] \times 10^{-3} \textit{ Dfl}$$

Assuming the risk aversion factor u equals 1, i.e. risk aversion is not considered, a first approximation of the break-even point for the trade-off factor b_0 equals

$$b_0 = - ev_m/ev_f \approx 50/1.7 \times 10^{4} \approx 290{,}000 \textit{ Dfl/fatality}$$

The tunnel route is preferred if the trade-off factor b_{dm}, defined by the decision-maker, is larger than b_0. If the risk aversion factor $u > 1$ is taken into account, the break-even point for the trade-off factor b will increase.

2.4 Perform sensitivity analysis

After the preceding three steps a choice between the alternatives can be made. It is important however to get insight into the robustness of this choice. In practice, decision-making processes often takes the form of an iterative procedure, in which sensitivity analyses are used to ensure that the essential characteristics of the decision problem under consideration get most of the attention. By performing sensitivity analyses it becomes possible to investigate the impact of input data variations on the outcome of the quantitative risk analysis calculations and on the parameters that are derived from this result, i.e. differences between the alternatives, break-even points and preference conditions. Thus it can be determined:

- whether the final results change significantly due to possible input data variations;
- whether factors exist, which require further investigation because they can have significant impact on the final results;
- what the impact on the final results is, if factors are corrected, e.g. in case new data becomes available.

Improvement of safety measures

The improvement of safety measures, both technical and organisational, will reduce specific accidents probabilities, the size of the associated damage etcetera. The result will lower the EV- and ELA-factors. Besides, these measures can change the expected value differences (ev- and ela-values) and, thus, can influence the outcome of the decision model.

Interviews with managers and specialists from subway companies show that the infrastructure is regarded as one of the most important aspects for an effective evacuation as well as for fire fighting [Verwoerd & Verheij, 1994]. This factor includes escape routes, signing, communication systems, emergency lights, emergency electricity supply, water supply for fire fighting etcetera. It is recommended to define the safety requirements during the design phase. From TNO's point of view a good design of the infrastructure is required to reach a high level of safety in a cost-effective way [Verwoerd & Verheij, 1995]. It will reduce the size of the consequences of accidents, especially accidents with release of hazardous materials.

Other measures to improve the safety of and in road tunnels after the tunnel has been built are posting traffic lights, installing smoke and/or fire detection systems, implementing monitoring and guiding systems etcetera.

The expected values will also change due to changes in the following input data:
- hazardous materials distribution across shipments;
- population densities;
- economic value densities;
- large accident threshold values.

The decision maker can change these input data in order to calculate the impact on the final result.

Relationship between different aspects

The treatment of the outcome is very difficult. Relationships have to be defined between fatalities and economic costs. It should be noted that the various methods for determining the value of a life have yielded a considerable range of values [see e.g. Graham & Vaupel, 1981]. This underlines the necessity of performing sensitivity analyses on this aspect.
One way to improve the quality of the decision-making process is to involve other parties or individuals. They can also evaluate an actual application which would enable the decision maker to take into account the preferences of the affected individuals.
Assigning weighing factors to the criteria then is an approved method to apply. This point will be discussed in section 4.

3. Application of the TNO decision model

The TNO decision model has been applied to a specific tunnel location. The lengths of the tunnel route and the diversion were 7.65 km and 15.9 km respectively. The results of the quantitative risk analysis calculations are presented in figure 3.
The tunnel route is preferred from the point of view of fatalities. Economic costs results do not show an unambiguous preference. Indicating the preferences by an asterisk it appears that this decision problem is a category 4A problem, see also paragraph 2.3.

	Tunnel	Diversion
EV_f	* 2.79	8.36
ELA_f	* 0.22	0.56

Figure 3a The results for the aspect 'fatalities', expressed in 10^{-7} fatalities/shipment.

	Tunnel	Diversion
EV_m	* 11.523	23.944
ELA_m	17	0

Figure 3b The results for the aspect 'economic costs', expressed in 10^{-3} Dfl/shipment.

Conditions indicating preference for alternative 1, the tunnel route, has been obtained from [Van Steen, 1987]. Substitution of the numbers calculated learns that the tunnel route is preferred if one of the following conditions is met:

- $u = 1 - ev_s/ela_s$ is smaller than ≈ 730;
- $b = - ela_m/ela_f$ is larger than ≈ Dfl 500,000 per fatality.

These conditions imply, that the tunnel route is preferred if large accidents are weighed less than 730 times as much as small accidents or if the economic costs that one is willing to accept to prevent a fatality is at least Dfl 500,000. These value judgments have to be made by the decision maker.

Concentrating on the contributions of the different categories of hazardous materials, it appeared that the expected values calculated were dominated by the flammable gases category. Figure 4 shows sensitivity analysis results when more specific information of accident probabilities is applied instead of standard values. The decision problem remains a category 4A problem. However, the conditions for the tunnel route preference change:

- $u \approx 2070$;
- $b \approx$ Dfl 290,000 per fatality.

	Tunnel	Diversion
EV_f	* 1.41	4.73
ELA_f	* 0.11	0.32

Figure 4a The results for the aspect 'fatalities', expressed in 10^{-7} fatalities/shipment, after application of sensitivity analysis.

	Tunnel	Diversion
EV_m	* 11.496	23.903
ELA_m	6	0

Figure 4b The results for the aspect 'economic costs', expressed in 10^{-3} Dfl/shipment, after application of sensitivity analysis.

If none of these conditions is met the decision problem becomes a category 4B problem. The joined effect of risk aversion and trade-off then determines the preference route.

4. Discussion

The present TNO decision model has demonstrated to be a powerful tool for decision-making processes on transport of hazardous materials through road tunnels. One application has already been mentioned in section 3. Other applications are the decision between several routes of the traject Ravenstein - Eindhoven [Jansen, 1991] and an expert opinion on on risks concerning the transport of hazardous materials along a roofed-in part of highway A2 at Leidsche Rijn [Wiersma et al., 1996]. The model has also been applied to compare the risks of two different designs of a tunnel connecting the Westerschelde banks [Jansen, 1995]. The designs were denoted:
- variant A; a tube with emergency doors to a transverse section every 100 m;
- variant B; a tube with emergency doors to a transverse section every 500 m.

The model, however, is also subject to a number of limitations. These are caused by the attributes considered, by the nature of the information available, by necessary simplifications and by the incorporation of value judgments. The sensitivity analyses performed in the present model may in some circumstances show that it is impossible or inadvisable to make a choice on the basis of the results calculated. Two situations may occur: one or more potentially variable factors may appear to be very influential, or the decision problem may be a borderline case. In those situations supplemental steps are to be considered. In the first case specific research into the factor in question might be possible. In the second case other aspects than fatalities and economic costs may be determining.

The use of a personal computer (instead of a desk calculator, see list of requirements in section 2) and the application of multi-criteria analysis techniques offers the possibilities to further develop the TNO decision model and, more important, the quality of the decision-making process. The advantages are:
- easy introduction of additional aspects such as environmental damage or public opinion;
- possibility of assigning weighing factors to each EV- and ELA-factor individually;
- easy recalculation of the results of the quantitative risk analysis when safety measures have been improved or new values concerning damage, effects or probability density functions of accidents are known.

4.1 Introduction of additional aspects

The key question is of interest both to existing routes and to new routes. Until several years ago the main criteria appeared to be limited to fatalities and economic costs. The environment, however, is of increasing importance and might therefore be an additional criterion. Also the public opinion can be a very important aspect in decision-making processes.

The application of multi-criteria analysis techniques will be required to improve the TNO decision model. It must be possible to develop the model, including the calculation rules and schemes of the present TNO decision model.

4.2 Assignment of weighing factors

As discussed in paragraph 2.4 relationships have to be defined between fatalities and economic costs in order to judge the choice between the alternatives. The number of relationships has to be extended if additional aspects are incorporated in the TNO decision model. This might be very complicating. The application of weighing factors will simplify this problem. Besides, a number of alternatives can be compared at once. Another advantage of applying weighing factors is the flexibility of assigning weighing factors to each of the individual EV- and ELA-factors. An example is given below.

Decision criteria and weighing factors w (numbers are given as an example):

- fatalities, expressed in number/shipment ($w_f = 0.85$):
  - EV_f ($w_{f,EV} = 0.10$);
  - ELA_f ($w_{f,ELA} = 0.90$).
- economic costs, expressed in Dfl/shipment ($w_m = 0.10$):
  - EV_m ($w_{f,EV} = 0.01$);
  - ELA_m ($w_{f,ELA} = 0.99$).
- environmental damage (e), expressed in emission/shipment ($w_e = 0.05$):
  - EV_e ($w_{e,EV} = 0.50$);
  - ELA_e ($w_{e,ELA} = 0.50$).

In this example the total expected value for fatalities contributes 10% to the 'fatalities result' (risk aversion factor $u_f = 9$) and 8.5% to the final result.
It is also possible to devide the subcriterion EV_f into an expected value for fatalities on the road and fatalities in the surroundings of the road. This point can also be regarded as a risk aversion problem. With the given approach these two expected values can be weighed different.

4.3 Improvements of safety measures

In general safety measures can be distinguished into:
- pro-active safety policy, e.g. transport of hazardous materials through tunnels or via diversion;
- prevention at the source, e.g. good tunnel design;
- corrective prevention, e.g. application of absorption materials;
- preparation, e.g. draw up an emergency response plan;
- repression, e.g. use of escape routes.

Decision problems such as the one described in this paper can, amongs others, be regarded as a safety measure of the first category.
Technical measures to improve the safety of and in road tunnels after the tunnel has been built are posting traffic lights, installing smoke and/or fire detection systems, implementing monitoring and guiding systems etcetera. These measures correspond with safety measures from categories three (corrective prevention) and four (preparation).

From a study on the management of evacuation of crowded areas such as in large buildings, trains etcetera [Verwoerd & Verheij, 1994], it appeared that the three most important factors concerning preparation (emergency planning) are:
- operational skills, the capability to act in the desired way in conformity with the emergency plan and in the spirit of the emergency plan;
- an emergency plan with associated simple procedures and instructions tailored to the different functions, including (the structure of) tasks and responsibilities;
- communication and the effectiveness of warnings and instructions; the way of transferring information as well as the equipment involved have to be of an adequate quality.

These factors show strong similarities with the conditions listed in section 1. Knowledge on these factors is still improving and, thus, can improve the safety in tunnels among others.

Casuistry on accidents improves the knowledge about these risks. Measures to prevent undesirable events can be based on case histories. As safety is an important issue in the most divergent situations, risk reducing measures are taken to prevent persons, animals, the environment and valuable goods from undesirable events. In order to know what kind of safety measures in tunnels have to be taken knowledge about the potential risks is advisable. Learning from tunnel accidents will also contribute to the improvement of safety in tunnels.

Recently two projects has been started up in order to improve the safety of tunnels as well as for individuals present in these tunnels during emergency situations. These projects are closely related. One project is focused on the safety measures in tunnels and the criteria used during the design phase. The aim is to develop a safety policy for tunnel design. The other project relates to the stage a tunnel is used. This project is concentrating on the development of a quantitative risk analysis model. The result should be a framework of a decision support system based on an complete risk analysis model. From here a set of safety measures of a tunnel to be taken can be defined. The final reports are planned to be written before summer 1997.

5. Acknowledgement

Jacques van Steen and Cees Jansen provided important contributions to the development of the TNO decision model 'transport of hazardous materials through road tunnels'. Large parts of this paper is based on their work. The authors are grateful to the Rijkswaterstaat for their contributions to the development and applications of the decision model.

6. References

V.T. Covello,
The perception of technological risks: A literature review,
Technological Forecasting and Social Change 23 (1983) 285-297.

CTGG project teams Technical Aspects (TA) and Quantitative Risk Analysis (QRA),
Quantification of risk reducing measures by the bulk transportation of hazardous materials (in Dutch),
Commission of Transportation of Hazardous Materials, December 1992.

Department of Industrial Safety,
FACTS database on accidents involving hazardous materials,
TNO Environment, Energy and Process Innovation, Apeldoorn, continuous update.

J.D. Graham & J.W. Vaupel,
Value of a life: What difference does it make?,
Risk Analysis 1 (1981) 89-95.

C.M.A. Jansen & L.A.M. Janssen,
Hand book on the application of the decision model transport of hazardous materials through tunnels or diversions (in Dutch),
TNO report 82-012195, TNO Environmental and Energy Technology, Apeldoorn, June 1983.

C.M.A. Jansen,
Application of the decision model for the transport of hazardous materials applied on several alternative routes of the traject Ravenstein - Eindhoven,
TNO report 91-268, TNO Environmental and Energy Technology, Apeldoorn, September 1991.

C.M.A. Jansen, J. Hoeksma & C. Pietersen,
Decision model for the transport of dangerous substances and the provisions required in road tunnels,
Proceedings 1st Int. Conference 'Safety in Road and Rail Tunnels', Basel, Switzerland, 23-25 November 1992, pp. 199-212.

C.M.A. Jansen,
Comparison between two designs of the tunnel connection between the Westerschelde banks for the safety of the road-user (in Dutch),
TNO report R95-182, TNO Environmental and Energy Technology, Apeldoorn, June 1995.

R.L. Keeney & H. Raiffa,
Decisions with multiple objectives: Preferences and value trade-offs,
Wiley, 1976.

J.F.J. van Steen,
A methodology for aiding hazardous materials transportation decisions,
European J. of Operational Research 32 (1987) 231-244, Elsivier Science Publishers B.V.

F.J. Verheij & T. Wiersma,
Decision support for company emergency response planning,
Proceedings 8th Int. Conference "Loss Prevention and Safety Promotion in the Process Industries', Antwerp, Belgium, 6-9 June 1995, Vol. II pp. 57-66.

M. Verwoerd & F.J. Verheij,
Modelling of Crowd Evacuations: The Development of the Management Tool,
TNO report 24551, TNO Environmental and Energy Technology, Apeldoorn, March 1995.

M. Verwoerd & F.J. Verheij,
Audit Guideline of Crowd Evacuations Management Systems (first draft),
TNO Environment, Energy and Process Innovation, Apeldoorn, December 1995.

T. Wiersma, M. Molag & C.M.A. Jansen,
Expert opinion on risks concerning the transport of hazardous materials along a roofed-in part of highway A2 at Leidsche Rijn (in Dutch),
TNO report 26693, TNO Environment, Energy and Process Innovation, Apeldoorn, October 1995.

D. de Weger, J.F.J. van Steen & F.J. Verheij,
Risk analytical methods - An overview (in Dutch),
TNO report 94-437, TNO Environmental and Energy Technology, Apeldoorn,
December 1994.

7. Authentication

Name and address of the principal
Bouwdienst Rijkswaterstaat
Postbus 20000
3502 LA Utrecht

Names and functions of the cooperators
F.J. Verheij
M. Molag

Names of establishments to which part of the research was put out to contract
-

Date upon which, or period in which, the research took place
February 1996

Signature

F.J. Verheij
research coordinator

Approved by

M. Molag
section leader