# Risk analysis and optimization of road tunnels

M. Holický
*Klokner institute, Czech Technical University in Prague, Czech Republic*

## Abstract

Probabilistic methods of risk optimization are applied to identify the most effective safety measures applied to road tunnels. The total consequences of alternative tunnel arrangements are assessed using Bayesian networks supplemented by decision and utility nodes. It is shown that the probabilistic optimization based on the comparison of societal and economic consequences may provide valuable information enabling a rational decision concerning effective safety measures. A general procedure is illustrated by the optimization of a number of escape routes. It appears that the discount rate and specified life time of a tunnel affect the total consequences and the optimum arrangements of the tunnels more significantly than the number of escape routes. The optimum number of escape routes is also significantly dependent on the ratio of cost of one escape routes and acceptable expenses for averting a fatality. Further investigation of relevant input data including societal and economic consequences of various hazard scenarios is needed.
*Keywords: tunnels, escape routes, risk optimization, Bayesian network.*

## 1 Introduction

Tunnel structures usually represent complex technical systems that may be exposed to hazard situations leading to unfavorable events with serious consequences. Minimum safety requirements for tunnels in the trans-European road network are provided in the Directive of the European Parliament and of the Council 2004/54/ES [1]. The Directive also gives general recommendations concerning risk management, risk assessment and analysis.

Methods of risk assessment and analysis are more and more frequently applied in various technical systems (Melchers [2], Stewart and Melchers [3] including road tunnels (Holický and Šajtar [4]). This is a consequence of recent tragic events in various tunnels and of an increasing effort to take into account

WIT Transactions on Ecology and the Environment, Vol 91, © 2006 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/RISK060061

societal, economic and ecological consequences of unfavorable events. Available national and international documents (NS [5], CAN/CSA [6], ISO [7], ISO [8], ISO [9] and ISO [10] try to harmonize general methodical principles and terminology that can be also applied in the risk assessment of road tunnels. The submitted contribution, based on previous studies (Vrouwenvelder et al. [11], Worm [12], Brussaard et al. [13], Vrouwenvelder and Krom [14], Kruiskamp et al. [15], Ruffin et al. [16] and Knoflacher and Pfaffenbichler [17]) and recent PIARC working documents, attempts to apply methods of probabilistic risk optimization using Bayesian networks supplemented by decision and utility nodes (Jensen [18]). It appears that Bayesian networks provide an extremely effective tool for investigating the safety of road tunnels.

## 2 Risk estimation

Probabilistic methods of risk analysis are based on the concept of conditional probabilities $P_{fi} = \mathrm{P}\{F|H_i\}$ of the event $F$ providing a situation $H_i$ occurs. In general this probability can be found using statistical data, experience or theoretical analysis of the situation $H_i$.

If the situation $H_i$ occurs with the probability $\mathrm{P}(H_i)$ and the event $F$ during the situation $H_i$ occurs with the conditional probability $\mathrm{P}(F|H_i)$, then the total probability $P_F$ of the event $F$ is given as

$$P_F = \sum_i \mathrm{P}(F \mid H_i)\mathrm{P}(H_i) \tag{1}$$

Equation (1) makes it possible to harmonize partial probabilities $\mathrm{P}(F|H_i)$ $\mathrm{P}(H_i)$ related to the situation $H_i$.

The main disadvantage of the purely probabilistic approach is the fact that possible consequences of the events $F$ related to the situation $H_i$ are not considered. Equation (1) can be, however, modified to take the consequences into account.

A given situation $H_i$ may lead to a set of events $E_{ij}$ (for example fully developed fire, explosion), which may have societal consequences $R_{ij}$ or economic consequences $C_{ij}$. It is assumed that the consequences $R_{ij}$ and $C_{ij}$ are unambiguously assigned to events $E_{ij}$. If the consequences include only societal components $R_{ij}$, then the total expected risk $R$ is given as

$$R = \sum_{ij} R_{ij}\mathrm{P}(E_{ij} \mid H_i)\mathrm{P}(H_i) \tag{2}$$

If the consequences include only economic consequences $C_{\mathrm{ij}}$, then the total expected consequences $C$ are given as

$$C = \sum_{ij} C_{ij}\mathrm{P}(E_{ij} \mid H_i)\mathrm{P}(H_i) \tag{3}$$

If criteria $R_{\mathrm{d}}$ and $C_{\mathrm{d}}$ are specified, then acceptable total consequences should satisfy the conditions

$$R < R_{\mathrm{d}} \text{ and } C < C_{\mathrm{d}} \tag{4}$$

that supplement the traditional probabilistic condition $P_f < P_{fd}$. However, up to now the criteria $R_d$ and $C_d$ are not well established and legally accepted.

When the criteria are specified and conditions (4) are not satisfied, then it may be possible to apply a procedure of risk treatment. For example additional escape routes, technological equipments and traffic restrictions may be considered. Such measures might, however, require substantial costs that should be taken into account when deciding about the optimum tunnel arrangements.

In general the criteria $R_d$ and $C_d$ indicated in equation (4) should be established on the basis of optimization shortly described below.

## 3 Principles of Risk optimization

The total consequences $C_{tot}(k,p,n)$ relevant to the construction and performance of the tunnel are generally expressed as a function of the decisive parameter $k$ (for example of the number $k$ of escape routes), discount rate $p$ (commonly about $p \approx 0{,}03$) and life time $n$ (commonly $n$ = 100 let). The decisive parameter $k$ usually represents a one-dimensional or multidimensional quantity significantly affecting tunnel safety.

The fundamental model of the total consequences may be written as a sum of partial consequences as

$$C_{tot}(k,p,n) = R(k,p,n) + C_0 + \Delta C(k) \tag{5}$$

In equation (5) $R(k,p,n)$ denotes expected societal risk that is dependent on the parameter $k$, discount rate $p$ and life time $n$. $C_0$ denotes the basic of construction cost independent of $k$, and $\Delta C(k)$ additional expenses dependent on $k$. Equation (5) represents, however, only a simplified model that does not reflect all possible expenses including economic consequences of different unfavourable events and maintenance costs.

The societal risk $R(k,p,n)$ may be estimated using the following formulae

$$R(k,p,n) = N(k)\ R_1\ Q(p,n), \quad Q(p,n) = \frac{1-1/(1+p)^n}{1-1/(1+p)} \tag{6}$$

In equation (6) $N(k)$ denotes number of expected fatalities per one year (dependent on $k$), $R_1$ denotes acceptable expenses for averting a fatality (or societal compensation cost (Rackwitz [19]), and $p$ the discount rate (commonly within the interval from 0 to 5 %). The quotient $q$ of the geometric row is given by the fraction $q = 1/(1+p)$. The discount coefficient $Q(p,n)$ makes it possible to express the actual expenses $R_1$ during a considered life time $n$ in current cost considered in (5). In other words, expenses $R_1$ in a year $i$ correspond to the current cost $R_1\ q^i$. The sum of the expenses during $n$ years is given by the coefficient $Q(p,n)$.

A necessary condition for the minimum of the total consequences (5) is given by the vanishing of the first derivative with respect to $k$ written as

$$\frac{\partial N(k)}{\partial k} R_1 Q(p,n) = -\frac{\partial \Delta C(k)}{\partial k} \tag{7}$$

In some cases this condition may not lead to a practical solution, in particular when the discount rate $p$ is small (a corresponding discount coefficient $Q(p,n)$ is large) and when the number of escape routes $k$ cannot be arbitrary increased.

## 4 Standardized consequences

The total consequences given by equation (5) may be in some cases simplified to a dimensionless standardized form and the whole procedure of optimization may be generalized. Consider as an example the optimization of the number $k$ of escape routes. It is assumed that involved additional costs $\Delta C(k)$ due to number of escape routes k may be expressed as the product $k\ C_1$, where $C_1$ denotes cost of one escape route then equation (5) becomes

$$C_{\text{tot}}(k,p,n) = N(k)\ R_1\ Q(p,n) + C_0 + k\ C_1 \tag{8}$$

This function can be standardized as follows

$$\kappa(k,p,n) = \frac{C_{tot}(k,p,n) - C_0}{R_1} = N(k)Q(p,n) + k\frac{C_1}{R_1} \tag{9}$$

Here $\zeta = C_1/R_1$ denotes the cost ratio. An advantage of standardized consequences is the fact that it is independent of $C_0$ and the cost ratio $\zeta = C_1/R_1$.

Both variables $C_{\text{tot}}(k,p,n)$ and $\kappa(k,p,n)$ are mutually dependent and have the extremes (if exist) for the same number of escape routes $k$. A necessary condition for the extremes follows from equation (7) as

$$\frac{\partial N(k)}{\partial k} = -\frac{C_1}{Q(p,n)R_1} = -\frac{1-1/(1+p)}{1-1/(1+p)^n}\frac{C_1}{R_1} \tag{10}$$

A first approximation may be obtained assuming that $C_1$ is in the order of $R_1$ (assumed also in a recent study by Vrouwenvelder and Krom [14]) where $C_1 \approx R_1 \approx 3$ MEUR), and then the cost ratio $\zeta = C_1/R_1 \approx 1$.

## 5 Model of a tunnel

The main model of a road tunnel is indicated in fig. 1. The tunnel considered here is partly adopted from a recent study by Vrouwenvelder and Krom [14]. It is assumed that the tunnel has the length of 4000 m and two traffic lanes in one direction. The traffic consists of heavy goods vehicles HGV, dangerous goods vehicles DGV and Cars. The main model includes three sub-models for heavy goods vehicles HGV, dangerous goods vehicles DGV and Cars. Fig. 2 shows a sub-model for dangerous goods vehicles DGV.

The total traffic intensity in one direction is $20\times10^6$ vehicles per year (27 400 vehicles in one lane per day). The number of individual types of vehicles is assumed to be HGV:DGV:Cars = 0,15:0,01:0,84.

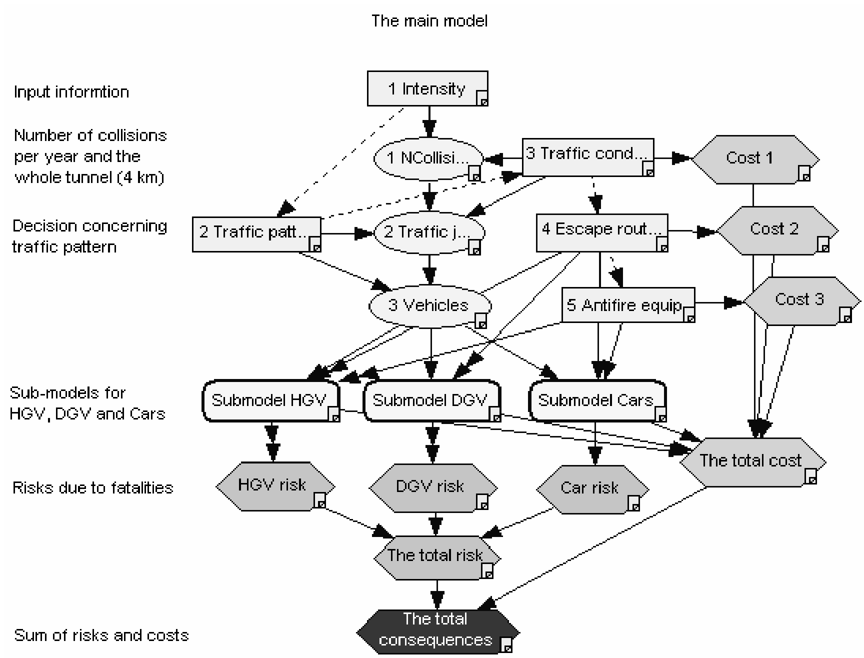


Figure 1: Main model of the tunnel.

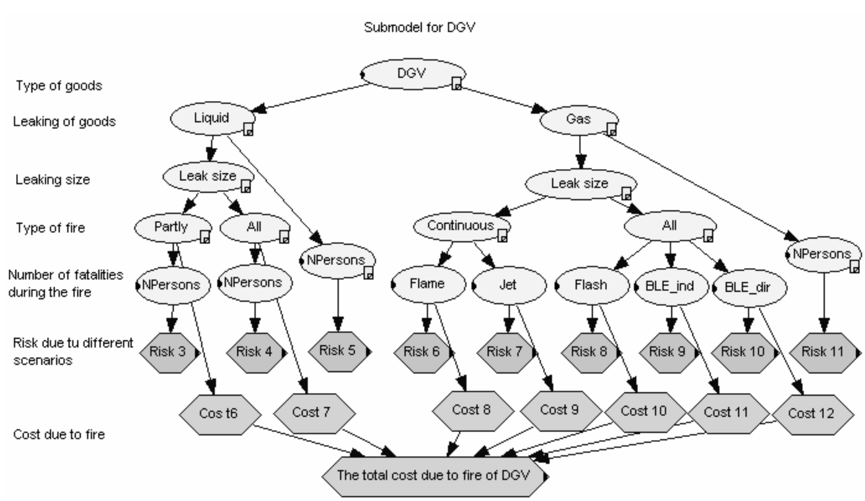


Figure 2: Sub-model for dangers goods vehicles DGV.

The frequency of serious accidents assuming basic traffic conditions (that might be modified) is considered as 1 $\times 10^{-7}$ per one vehicle and one km (Vrouwenvelder and Krom [14]), thus 8 accidents in the whole tunnel per year. The Bayesian networks used here need a number of other input data. Some of them are adopted from the study by Vrouwenvelder and Krom [14] (based on event tree method), the other are estimated or specified using expert judgment. Note that different types of hazard scenarios are distinguished as they may cause different consequences. Similar sub-models are used also for heavy goods vehicles HGV and Cars.

## 6 Risk optimization

Risk optimization of the above described tunnel is indicated in Fig. 3, 4 and 5 showing variation of the standardized total consequences $\kappa(k,p,n)$, given by equation (9) with number of escape routes $k$ for selected discount rates $p$ (up to 5 %) and life time $n$ (= 50 and 100 years) assuming the cost ratio $\zeta = C_1/R_1 \approx 1$.

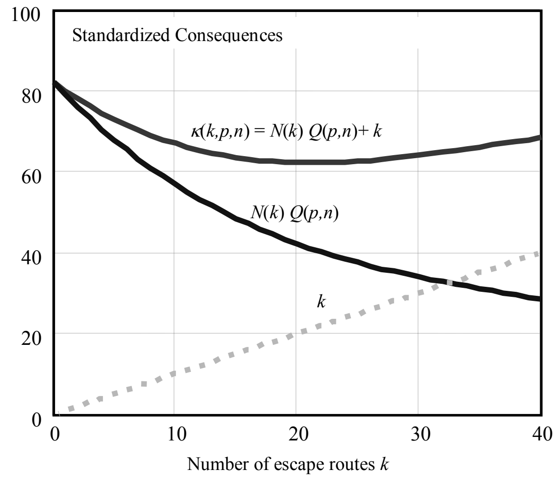


Figure 3: Variation of the components of standardized total consequences $\kappa(k,p,n)$ with $k$ for the discount rate $p$ = 0,03, the cost ratio $\zeta = C_1/R_1 = 1$ and life time $n$ = 100 years.

Fig. 3 shows the variation of the components of standardized total consequences $\kappa(k,p,n)$ with the number of escape routes $k$ for a common value of the discount rate $p$ = 0,03 and the assumed life time $n$ = 100 years. Fig. 4 shows the variation of the standardized total consequences $\kappa(k,p,n)$ with $k$ for selected discount rates $p$ and the life time $n$ = 50 years only. Fig. 5 shows similar curves as fig. 4 but for the expected life time $n$ = 100 years (common value).

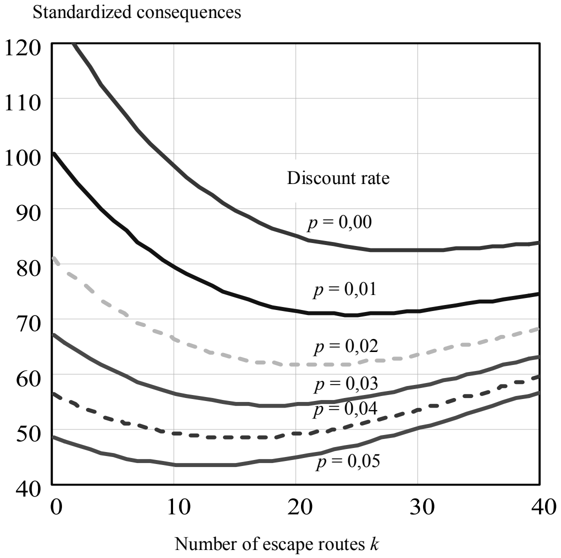


Figure 4: Variation of the standardized total consequences $\kappa(k,p,n)$ with $k$ for the cost ratio $\zeta = C_1/R_1 = 1$, selected discount rates $p$ and the life time $n = 50$ years.

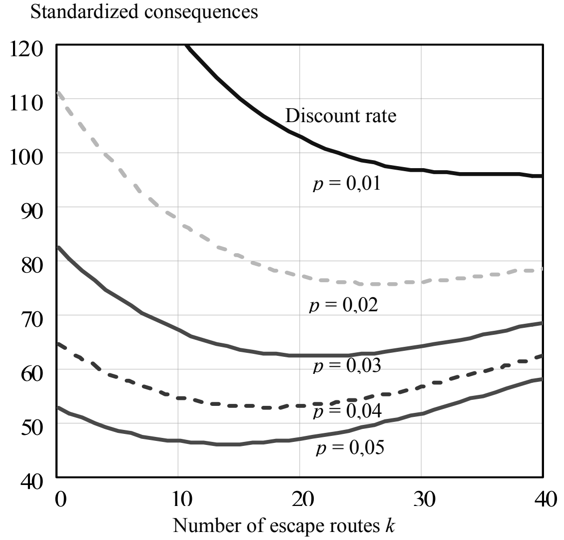


Figure 5: Variation of the standardized total consequences $\kappa(k,p,n)$ with $k$ for selected discount rates $p$, the cost ratio $\zeta = C_1/R_1 = 1$ and the life time $n = 100$ years.

## 7 Effect of the cost ratio $\zeta = C_1/R_1$

The cost ratio $\zeta = C_1/R_1$ may also affect the optimum number of escape routes. Note that the approximations $\zeta = C_1/R_1 \approx 1$ assumed above was recently accepted in the study (Vrouwenvelder and Krom [14]) (where the cost $C_1 \approx R_1 \approx 3$ MEUR is mentioned). Fig. 6 shows variation of the total standardized consequences with the number of escape routes $k$ for selected cost ratios $\zeta$ (considered within the interval from 0,5 to 2), the discount rate $p$ = 0,03 and life time $n$ = 100 years.

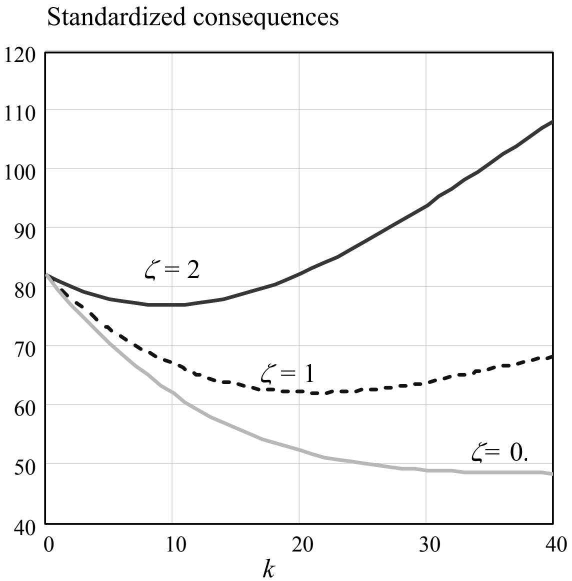


Figure 6: Variation of the standardized total consequences $\kappa(k,p,n)$ with the number of escape routes $k$ for selected cost ratios $\zeta$, the discount rates $p$= 0,03 and for the life time $n$ = 100 years.

It follows from fig. 6 that the optimum number of escape routes $k$ is significantly dependent on the cost ratio $\zeta = C_1/R_1$. In general the optimum number of escape routes $k$ increases with decreasing cost ratio $\zeta$, i.e. with increasing expenses $R_1$ (an expected result). For example for $\zeta = 2$ the optimum $k$ is about 9, for $\zeta = 1$ the optimum $k$ is about 20 and $\zeta = 0{,}5$ the optimum $k$ is more than 40. The last case seems to be unrealistic solution (it would lead to a distance of escape routes less than 100 m).

## 8 Conclusions

The following conclusions may be drawn from the submitted study of probabilistic risk optimization of road tunnels using Bayesian networks:

- Probabilistic risk optimization may provide background information valuable for a rational decision concerning effective safety measures applied to road tunnels.
- It is shown that the optimum number of escape routes may be specified from the requirement for the minimum of total consequences covering both the societal and economic aspects.
- The optimum number of escape routes depends generally on discount rate, required life time and the ratio between the cost for one escape route and acceptable expenses that a society is able to afford for averting one fatality (societal compensation cost).
- It appears that the total consequences are primarily affected by the discount rate and less significantly by assumed life time, cost ratio and the number of escape routes.
- Bayesian networks supplemented by decision and utility nodes seem to provide an effective tool for risk analysis and optimization.
- Further investigations of relevant input data concerning conditional probabilities describing individual hazard scenarios and models for their societal and economic consequences are needed.

## Acknowledgement

This study is a part of the project GAČR 103/06/1521 „Reliability and Risk Assessment of structures in Extreme Conditions“ supported by The Grant Agency of the Czech Republic.

## References

[1] Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the trans-European road network. Official Journal of the European Union L 201/56 of 7 June 2004.
[2] R.E. Melchers, *Structural reliability analysis and prediction*, John Wiley & Sons, Chichester, 437 p., 1999.
[3] Stewart M.S. & Melchers R.E. *Probabilistic risk assessment of engineering system*, Chapman & Hall, London, 274 p., 1997.
[4] Holický M. & Šajtar L. Risk Assessment of road tunnels based on Bayesian network, *Proc. of the Advances in Safety and Reliability, ESREL 2005*, Taylor & Francis Group, London, pp. 873-879, 2005.
[5] NS 5814, 1991, Requirements for risk analysis, 1991.
[6] CAN/CSA-Q634-91, Risk analysis requirements and guidelines, 1991.
[7] ISO 2394, General principles on reliability for structures, ISO, 1998.
[8] ISO/IEC Guide 73, Risk management – Vocabulary - Guidelines for use in standards, 2002.
[9] ISO/IEC Guide 51, Safety aspects – Guidelines for their inclusion in standards, ISO/IEC, 1999.

[10] ISO 9000, Quality management systems – Fundamentals and vocabulary, ISO, 2000.

[11] Vrouwenvelder A., Holický M, Tanner C.P., Lovegrove D.R. & Canisius E.G. *Risk assessment and risk communication in civil engineering*, CIB Report Publication 259, 2001.

[12] Worm E.W. Safety concept of Westershelde tunnel, manuscript provided by SATRA, Prague, 2002.

[13] Brussaard L.A., Kruiskamp M.M. & Oude Essink M.P. The Dutch model for the quantitative risk analysis of road tunnels, *Proc. of the ESREL conference*, Berlin, 2004.

[14] Vrouwenvelder A.C.W.M. & Krom A.H.M. Hazard and the Consequences for Tunnels Structures and Human Life, *Proc. of the 1st International Symposium Safe and Reliable Tunnels in Prague*, CUR, Gouda, The Netherlands, pp. 23-32, 2004.

[15] Kruiskamp M.M., Weger D. de & Hoeksma J. TUNprim: A Spreadsheet model for the calculating road tunnels risk, *Tunnels Management International*, Volume 5, Number 1, pp. 6 – 12, 2002.

[16] Ruffin E., Cassini P. and Knoflacher H. *Transport of hazardous goods,* Chapter 17 of Beard A and Carvel R, *The Handbook of Tunnel Fire Safety.* Thomas Telford Ltd, London, pp. 354-387, 2005.

[17] Knoflacher H. & Pfaffenbichler P.C. A comparative risk analysis for selected Austrian tunnels, *Proc. of the 2nd International Conference Tunnel Safety and Ventilation*, Graz, 2004.

[18] Jensen V. *Introduction to Bayesian networks*, Aalborg University, Denmark, 1996.

[19] Rackwitz R. The philosophy Behind the Life quality Index and Empirical Verification, Working material of JCSS, 2005.