RISK ASSESSMENT AND OPTIMIZATION OF ROAD TUNNELS

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Abstract

Probabilistic methods of risk optimization are applied to specify the most effective arrangements of road tunnels. The total consequences of alternative arrangements are assessed using Bayesian networks supplemented by decision and utility nodes. It appears that the optimization may provide valuable information for a rational decision concerning number of escape routes. Discount rate seems to affect the total consequences and the optimum arrangements of the tunnels more significantly than number of escape routes.

Key words

Risk assessment, social risks, economic consequences, road tunnels, Bayessian network, optimization, escape routes, discount rate, expected life time

INTRODUCTION

Tunnel structures usually represent complex technical systems that may be exposed to hazard situations leading to unfavourable 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 recommendations concerning risk management, risk assessment and analysis.

Methods of risk assessment and analysis are more and more frequently applied in various technical systems [2,3] including road tunnels [4]. This is a consequence of recent tragic events in various tunnels and of an increasing effort to take into account social, economic and ecological consequences of unfavourable events [2,3,4]. Available national and international documents [5] to [10] try to harmonise general methodical principles and terminology that can be also applied in the risk assessment of road tunnels. The submitted contribution, based on previous studies [11] to [17] and recent PIARC working documents, attempts to apply methods of probabilistic risk optimization using Bayesian networks supplemented by decision and utility nodes [18]. It appears that Bayesian networks provide an extremely effective tool for investigating the safety of road tunnels.

GENERAL PROCEDURE OF RISK ASSESSMENT

The main components of the whole risk management consist of risk assessment and risk control. The risk control is outside the scope of this paper. The risk assessment consists of risk analysis and risk evaluation. A general procedure of risk assessment is shown in Figure 1 indicating a flowchart of the main steps. The flowchart is adopted from ISO document [9] and from recent working materials of PIARC/C3.3/WG2. The contents of individual steps are mostly obvious from the relevant key words used for description of the flowchart. Two key steps of the risk analysis, probability analysis and risk estimation are shortly described below.

PROBABILITY ANALYSIS

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 [1, 3]. 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 probability $\mathrm{P}(F|H_i)$, then the total probability P_F of the event F is given as

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

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.

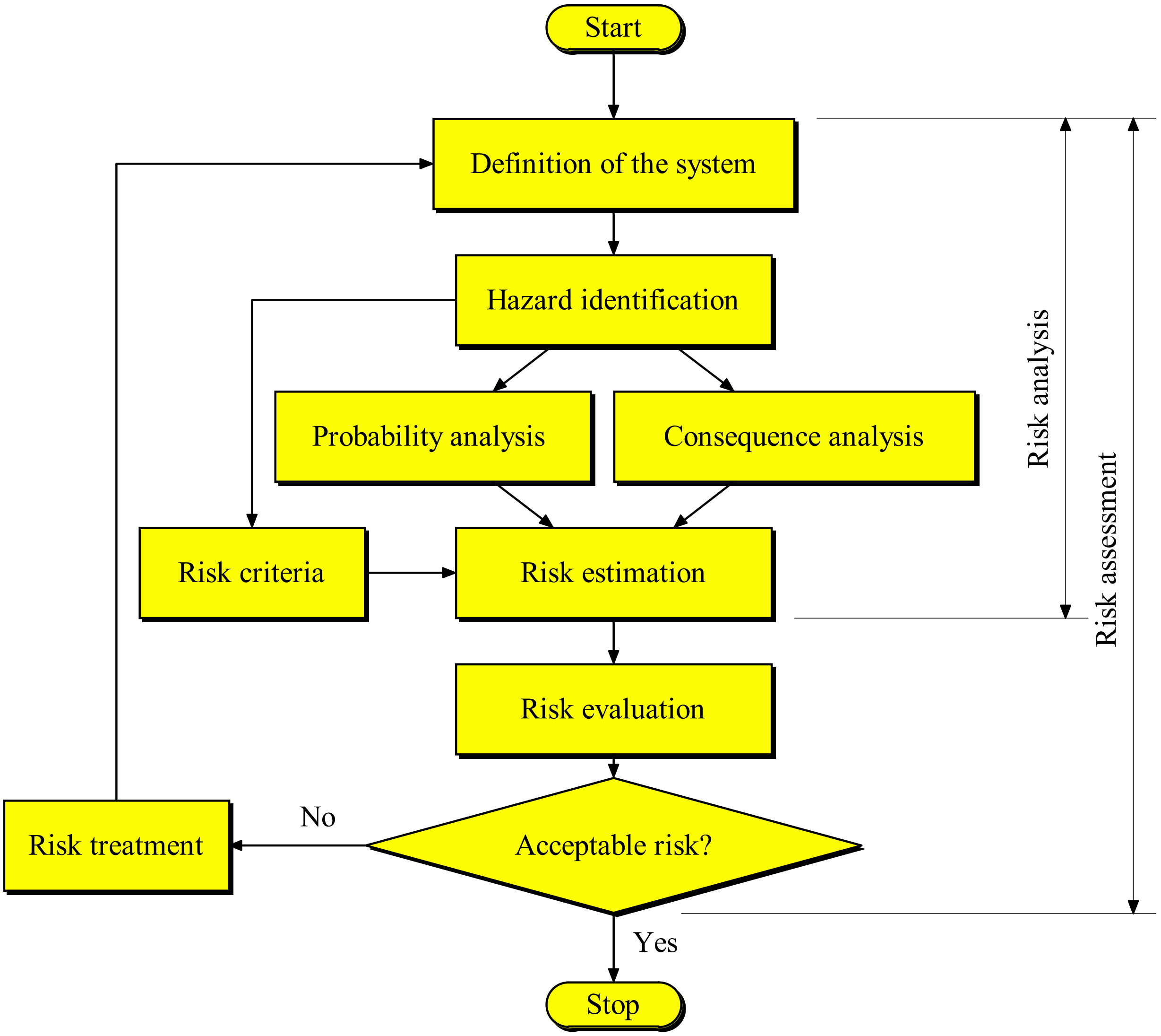

Figure 1. Flowchart of iterative procedure for the risk assessment (adopted from [9])

RISK ESTIMATION

A given situation H_i may lead to a set of events E_{ij} (for example fully developed fire, explosion), which may have social 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 social components R_{ij}, then the total expected risk R is given as [11]

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

If the consequences include only economic consequences C_{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_d and C_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 $P_\mathrm{f} < P_\mathrm{fd}$.

When the criteria are not satisfied, then it may be possible to apply a procedure of risk treatment as indicated in Figure 1. For example additional escape routes may be provided. Such measures might, however, require considerable costs, which should be considered when deciding about the optimum measures.

PRINCIPLES OF RISK OPTIMIZATION

The total consequences $C_\mathrm{tot}(k,p,n)$ 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

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

In equation (5) $R(k,p,n)$ denotes expected social 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 social risk $R(k,p,n)$ may be estimated using the following formulae

$$R(k,p,n) = N(k)\, Z_1\, Q(p,n), \quad Q(p,n) = \frac{1 - 1/(1+p)^n}{1 - 1/(1+p)} \tag{6}$$

In equation (6) $N(k)$ denotes number of expected fatalities per one year (dependent on k), Z_1 denotes acceptable expenses for averting one fatality, 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 Z_1 during a considered life time n in current cost considered in (5). In other words, expenses Z_1 in a year i correspond to the current cost $Z_1\, q^\mathrm{i}$. 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 that may be written as

$$\frac{\partial N(k)}{\partial k} Z_1 Q(p,n) = -\frac{\partial \Delta C(k)}{\partial k} \tag{7}$$

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 there is a limited number of escape routes k that can not be arbitrary increased.

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 k may be expressed as the product $k\, C_1$, where C_1 denotes cost of one escape route. If C_1 is approximately equal to expenses Z_1 (assumed also in [14]), equation (5) may be written as

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

This function can be standardized as follows

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

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

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

An advantage of standardized consequences is the fact that it is independent of C_0 and C_1. It is only assumed that $C_1 \approx Z_1$ is a time invariant unit of the total consequences.

MODEL OF A TUNNEL

A road tunnel considered here (Figure 2) is partly adopted from a recent study [14]. It is assumed that the tunnel has the length of 4000 m and two traffic lanes in one direction are used by heavy goods vehicles HGV, dangers goods vehicles DGV and Cars.

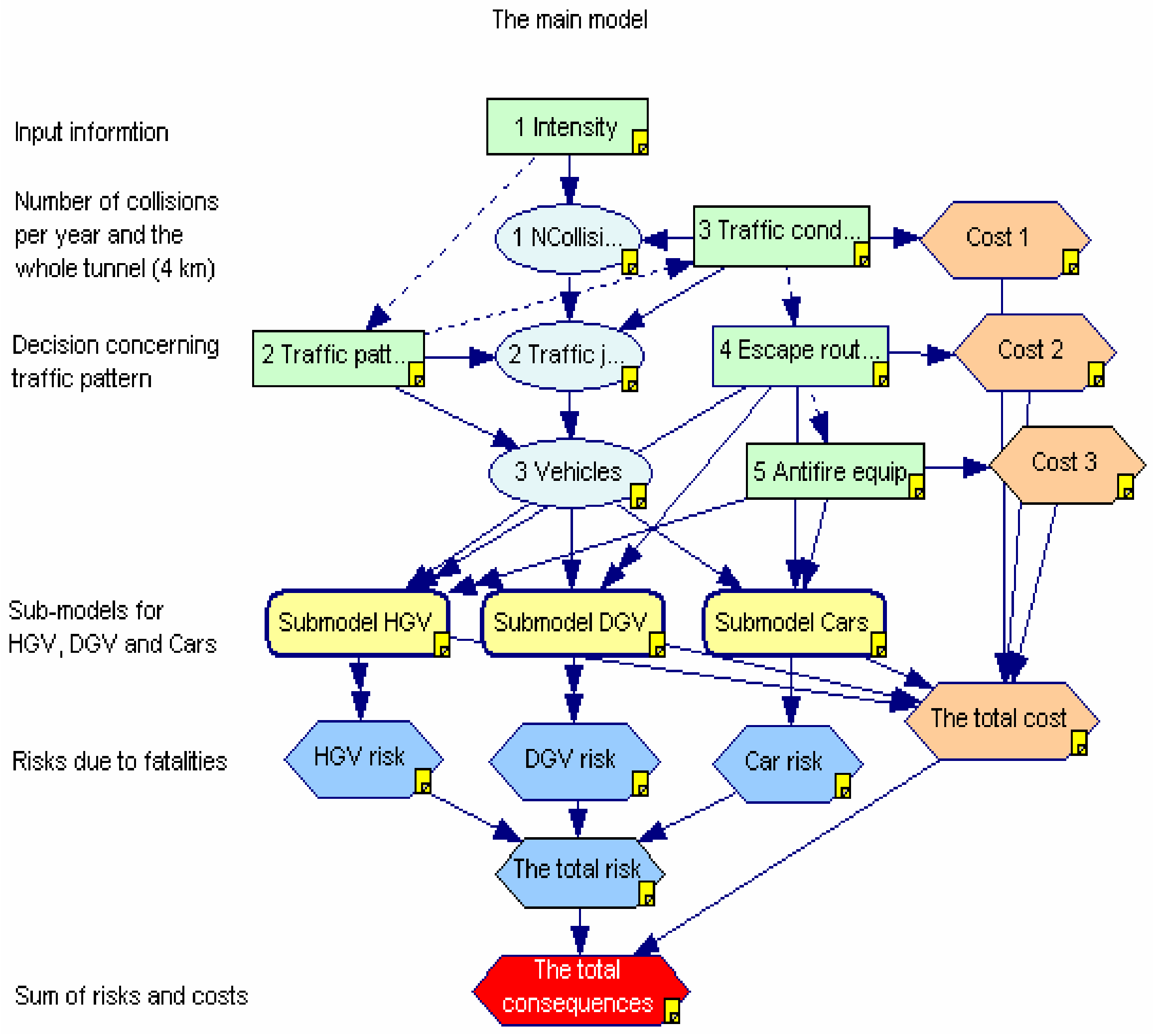

Figure 2. Main model of the tunnel

The total traffic intensity in one direction is 20×10^6 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. The frequency of series accidents for basic traffic conditions (that might be possibly improved) is considered as 1×10^{-7} per one vehicle and one km [14], thus 8 accidents in the tunnel per year.

The main model of the tunnel shown in Figure 2 includes three sub-models for HGV, DGV and Cars, which describe individual hazard scenarios. The Bayesian networks used here need a number of other input data. Some of them are adopted from the study [14] (based on event tree diagram), the other are estimated or specified using expert judgement. Detailed description of the model is outside the scope of this contribution.

RISK OPTIMIZATION

Risk optimization of the above described tunnel is indicated for selected input data in Figure 3, Figure 4 and 5. Figure 3 shows variation of the components of standardized total consequences $\kappa(k,p,n)$ with number of escape routes k for a common value of the discount rate p = 0,03 and assumed life time n = 100 years.

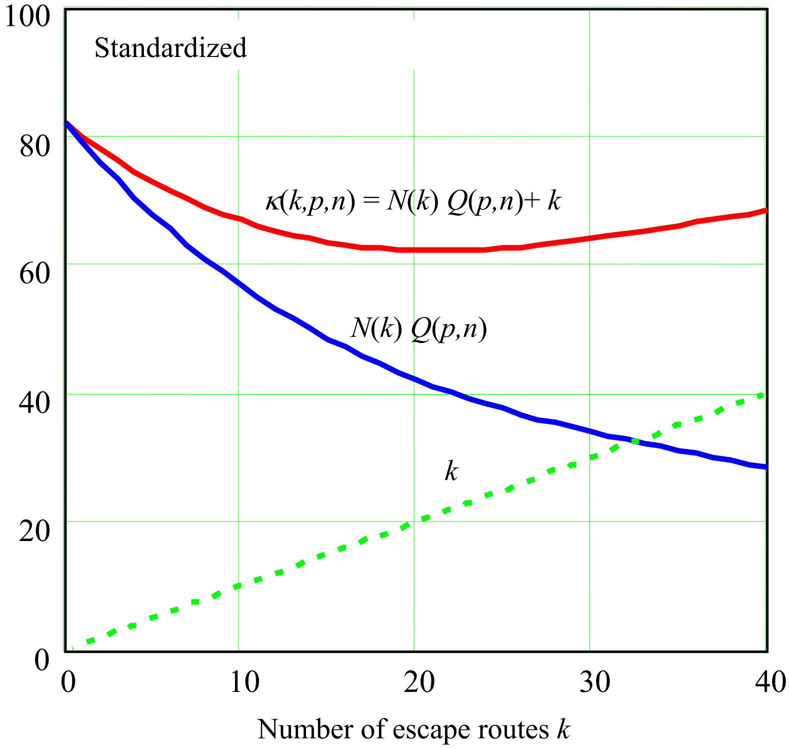

Figure 3. Variation of the components of standardized total consequences κ(k,p,n) with k for the discount rate p = 0,03 and life time n = 100 years

Figure 4 shows variation of the standardized total consequences $\kappa(k,p,n)$ with k for selected discount rate p life time n = 50 years only, Figure 5 shows similar curves as Figure 4 but for expected life time n = 100 years (common value). Both Figures 4 and 5 clearly indicate that the discount rate p and life time n affect the total consequences more significantly than the number of escape routes k. It appears that the total consequences considerably increase with increasing n. For small discount rates $p \leq 0.01$ and life time n = 100 years the total consequences decrease monotonously with increasing k and for $k \leq 39$ (the distance of escape routes up to 100 m) do not reach its minimum. Therefore, in this case condition (10) does not lead to a practical solution.

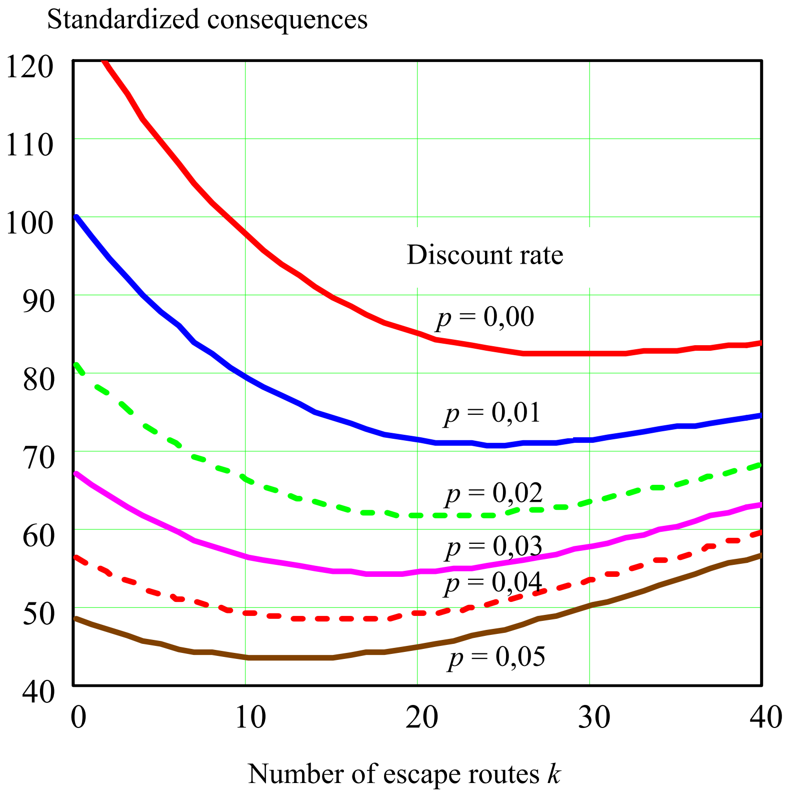

Figure 4. Variation of the standardized total consequences κ(k,p,n) with k for selected discount rate p life time n = 50 years

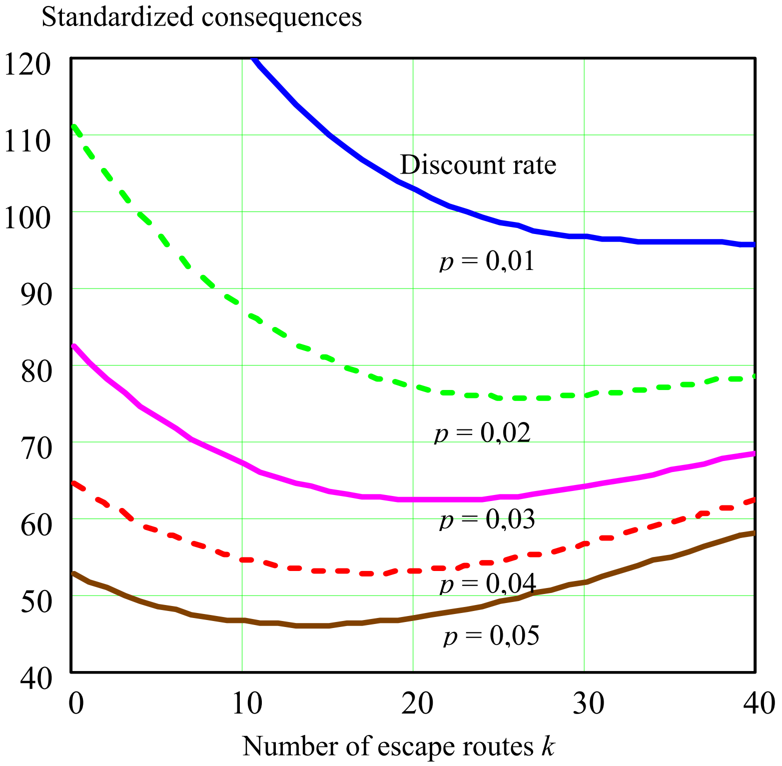

Figure 5. Variation of the standardized total consequences κ(k,p,n) with k for selected discount rate p life time n = 100 years

Figure 6 shows variation of the total consequences $\kappa(k,p,n)$ with number of escape routes k and discount rate p assuming again expected life n = 100 years.

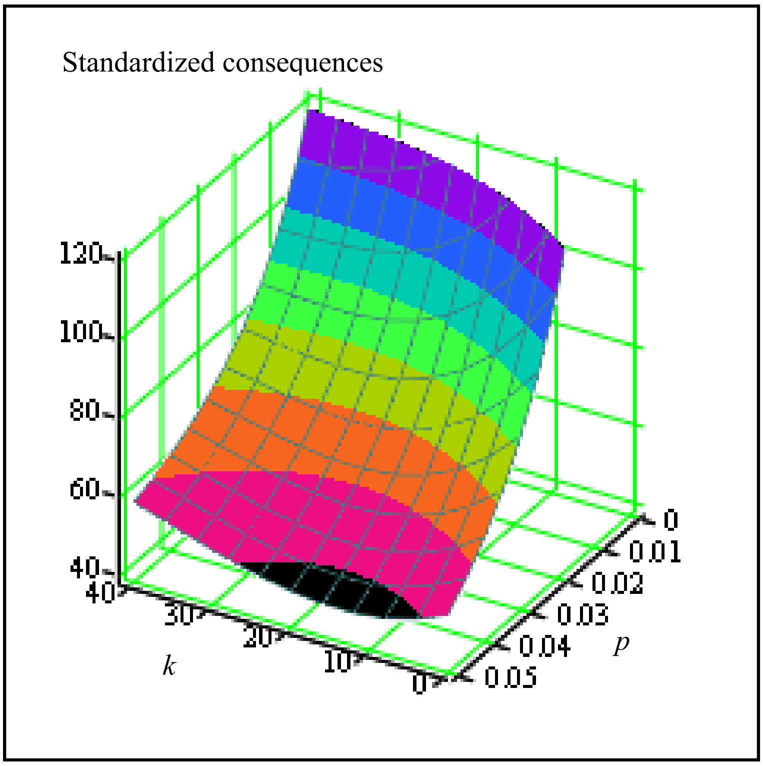

Figure 6. Variation of the standardized total consequences $\kappa(k,p,n)$ with k for selected discount rate p life time n = 100 years

Figure 6 clearly illustrates previous finding that the discount rate p affects the total consequences $\kappa(k,p,n)$ more significantly than the number of escape routes k.

CONCLUSIONS

Similarly as in case of other technical systems the risk assessment of road tunnels commonly includes

- definition of the system
- hazard identification
- probability and consequences analysis
- risk evaluation and possible risk treatment

Two kinds of criteria commonly applied in the risk assessment of road tunnels relate to:

- expected individual risk
- cumulative social risk (fN curves)

Probabilistic risk optimization based on the comparison of social and economic consequences may provide background information valuable for a rational decision concerning effective safety measures of road tunnels. It appears that the discount rate and assumed life time may affect the total consequences and the optimum arrangements of the tunnels more significantly than the number of escape routes. However, further investigations of relevant input data concerning social and economic consequences are needed.

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