HAZARDS AND THE CONSEQUENCES FOR TUNNEL STRUCTURES AND HUMAN LIFE

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ABSTRACT

Accidents in tunnels and other underground structures often lead to serious consequences, more serious in general than would have been the case in open air. For this reason careful consideration of safety and structural integrity during design, execution and exploitation is necessary. The paper shows the results of the EU sponsored Durable and Reliable Tunnel Structures (DARTS) research project that has focused on rational design methods. The emphasis will be on a risk analysis approach to hazards, in particular fire.

1. INTRODUCTION

Tunnels and underground structures are indispensable when installing new infrastructure in congested areas as well as when raising the quality of existing urban living. Tunnels, however, are expensive structures to build and mistakes may lead to serious consequences for the various stakeholders, both during construction and later in the exploitation stage. Particular issues are the possible high costs of maintenance, damage and protection to the environment and consequences of hazards both during execution and exploitation. The EU project DARTS (Durable and Reliable Tunnel Structures) was intended to develop operational methods and practical tools for choosing a cost optimal tunnel type and construction procedure. The dominating feature of DARTS is the integration of reliability based design, service life design, risk assessment and environmental and economic aspects [1]. An overview of work packages and involved partners is presented in Annex A. The present paper deals primarily with the hazard aspects of tunnel design, in particular fire.

2. DESCRIPTION OF HAZARDS

A hazard may be defined as a possible event that has the potential to do harm. Both the probability that the event occurs as well as the consequences depend on the circumstances. In present day tunnel design the issue of hazards is treated in many different ways. For some projects a fairly advanced approach on the basis of risk analysis is being made, while for other projects hardly justified deemed to satisfy rules are being used. The DARTS research project has aimed at the development of a rational approach for taking hazards into account on the basis of economic cost optimisation.

In order to estimate the hazard related costs qualification and quantification (models, statistics) of the following aspects is [1]:

- initiating events (causes) and subsequent hazard scenarios
- consequences (damage , casualties as well as their monetary equivalents)
- probabilities for all events
- effects of risk reducing measures

Models for hazard scenarios
At the start of a project usually a qualitative risk model is built, describing the relevant initiating events, the various follow up events as well as the effects of possible mitigating actions. A sequence of a possible set of events and actions is often referred to as a hazard scenario. In the case of a fire, for instance, the initiating event may be a lorry defect leading to a release of fuel and some spark to start the actual fire. The subsequent burning process will then lead to the actual events like smoke and increased temperatures. The process may be influenced by sprinkler installations, fire brigade actions, etc. For some hazards a qualitative approach may be sufficient. For other cases quantitative and physical models may be necessary.

Consequences
The next step in the model concerns the description of consequences in terms of casualties, injuries, material losses, environmental losses and structural damage. The effect of rescue measures plays of course an important role and should be part of the modelling. The consequence analysis shall consider both immediate consequences and those that arise after a certain time has elapsed. In order to find optimal solutions one should be able to express all items into one unit. It will be assumed here that monetary values provide a consistent and rational basis for decision making.

Probabilities
Data is needed as input for the models in terms of probabilities of occurrence (or frequencies) for the initiating events, conditional probabilities for follow up events and probability density functions for the various physical parameters. In many cases, however, proper and detailed data is lacking and the designer may only rely on rough estimates.

Mitigating measures
In order to reduce the risk involved in accidental type of loading situations one might, as a basic strategy, consider probability reducing as well as consequence reducing measures, including contingency plans in the event of an accident. Design with respect to accidental actions may therefore pursue one or more of the following strategies, which may be combined in the same design:

1. preventing the action/event to occur or at least reducing the probability of it occurring
2. preventing the action/event to grow or to reach extreme levels (e.g. sprinkler installations)
3. non-structural measures to resist the action (e.g. by barriers against collisions)
4. structural measures to resist the action (strength of the structure)
5. mitigating the consequences (ventilation, evacuation, rescue, quick repair)

The strategy or combination of strategies to be chosen depends on the cost effectiveness.

3. PRESENTATION OF A HAZARD ANALYSIS

A risk analysis may be performed and presented in various ways. A very common way is to present the hazards in the form of a Failure Mode and Effect Analysis (*FMEA*). In principle this is a list of all possible unwanted events, their causes and consequences. In most cases the probabilities and consequences are quantified. Based on this information one may decide which parts will be elaborated further. A more detailed way of presentation is shown in Figure 1. In the centre there is the so called "abnormal" or "unplanned" event. The various possible causes for this abnormal event are usually presented in a *fault tree*. The set of circumstances leading to different types or different intensities of consequences are represented in an *event tree*. For all branches of the fault tree and the event tree probabilities can be estimated. Counter measures and their effects can be indicated.

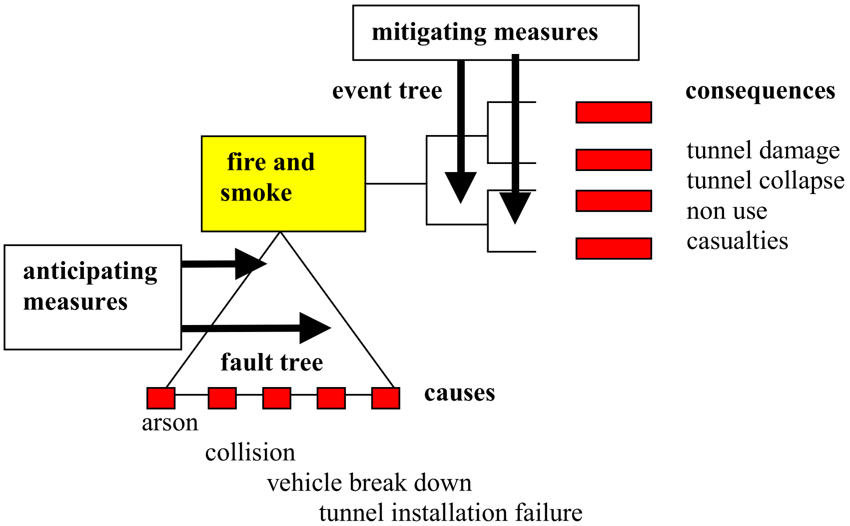

Figure 1 Basic presentation of event sequences during a fire [3]

Consequences and probabilities may be expressed in various ways. The most common way is to start in early design stages with some kind of classification only (for example low, medium. large). In the more detailed design steps and for selected aspects, a full risk analysis on the basis of best estimates for probabilities and consequences will be made. First only consequences in "physical units" will be calculated, like "damage to the tunnel", hours of non-use and number of casualties. Later on a translation into monetary values is required in order to enable rational and optimal decisions. A difficulty is to express non-monetary items, like human lives, in monetary values. Such a value, of course, should not be understood a "the value of the life of a human beings" but "a number to be used in order to get consistency in the decision process".

4. COST OPTIMAL DECISION MAKING

The design process should aim for the cost optimal solution, considering however all socio-economic aspects of the planned or existing tunnel.

This means that one should try to minimise:

$$E(C) = E\{C_{building} + C_{maintenance} + C_{exploitation} + C_{hazards} + C_{demolition}\} \quad (1)$$

where the symbol E indicates "Expectation" or "Average Value" and C_i indicates the costs. All future costs should be discounted to a present value. The hazard related costs $C_{hazards}$ are in DARTS referred to as the "*risk add-on*". The risk add-on can be considered as the remaining risk after possible measures. We may elaborate this term for the hazard fire as:

$$C_{fire} = \lambda_F F_{cap} \{E(N_c)\, C_c + E(C_R) + E(C_{nu})\} \quad (2)$$

where λ_F is the probability of having a (serious) fire per time unit, F_{cap} the capitalisation factor depending on the discount rate and the time period considered, C_c the costs related to a casualty, N_c the number of casualties in case of fire, C_R the costs of repair and C_{nu} the costs of non-use (out-of-service) in case of damage.

5. RISK ANALYSIS FOR FIRE

5.1 Introduction

Although tunnels may have to endure many types of hazard (for instance explosion, earthquake, flooding, dropping ship anchors, etc) fire seems to be the most severe one. For this reason we will concentrate on fire in this paper. The set of models needed to estimate the expected values of the various consequences are:

- fault and event tree models to estimate intensity and frequency of fire;
- a model to estimate the temperature-time relation in the fire compartment;
- a thermal model to find the effects of high temperature on the structure;
- a structural response model to estimate deformations, stresses and damage;
- models for smoke development;
- models for human behaviour during fire.

Based on these models the consequences in the form of injuries, fatalities, damage and out-of-service time may be estimated in probabilistic terms. This result is the basis for the economic optimisation as introduced in Section 4. Two examples, a road and a railway tunnel will be examined.

5.2 Example 1: Cost effectiveness of fire safety measures in a bored road tunnel

This example is taken from DARTS WP5.2 report [2], chapter 5, that deals with the choice of a cut & cover and a bored road tunnel. Both tunnels consists of two tubes and each tube has two one-way lanes. In the bored tunnel the number of the emergency exits plays important role in the total costs. A simplified version of the TunPrim model [4,5] is used to investigate the influence of the distance between exits on the expected number of casualties. In this paper we consider only the casualties among the persons who try to escape from the fire (the 'fugitives') and not the casualties due to incident directly preceding the fire. It is assumed that these casualties are not affected by the tunnel type. Hence this assumption does not affect the decision on the tunnel type.

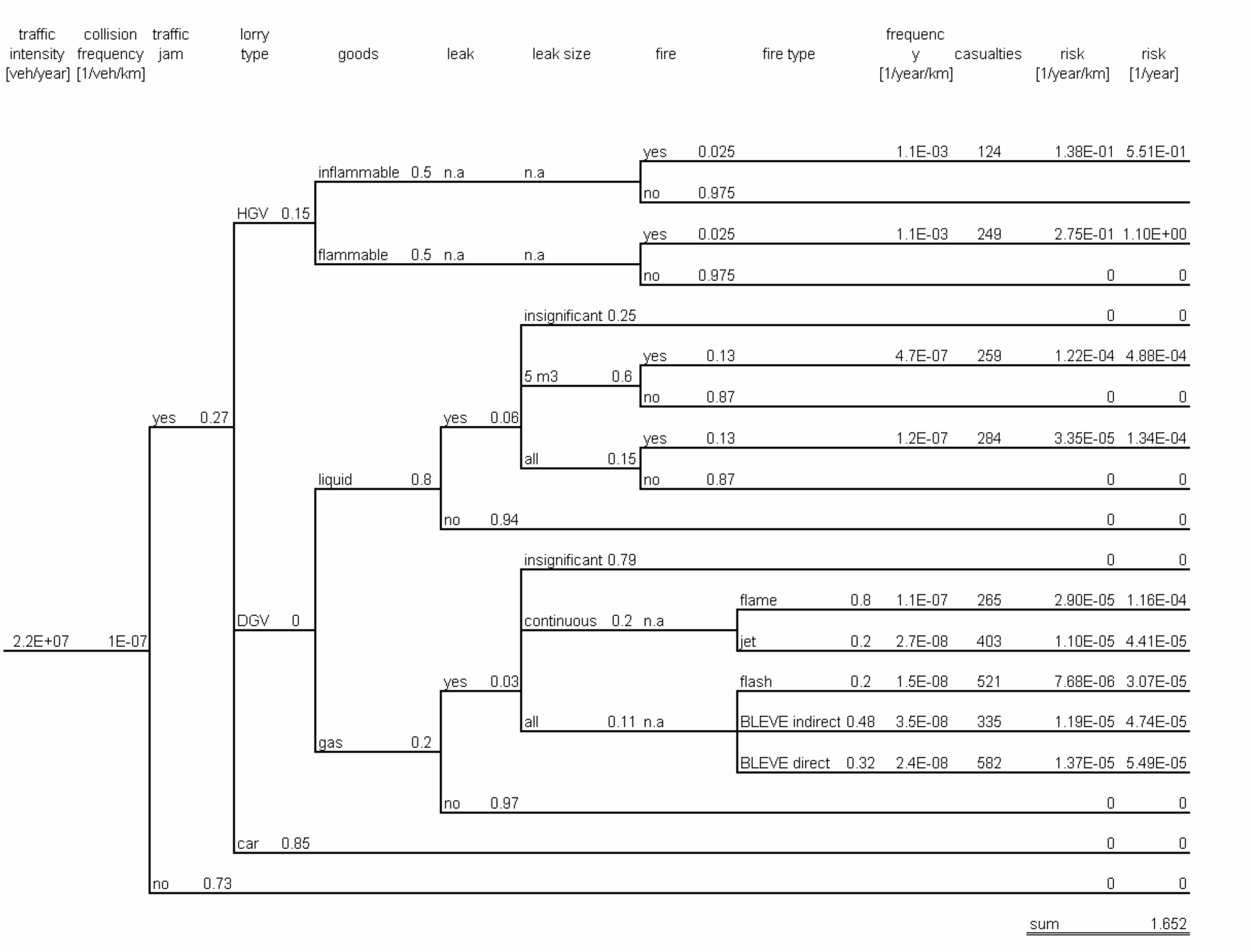

Figure 2 Event tree of the different fire scenarios in a tunnel including the probabilities and number of casualties for each scenario for an emergency exit distance of 1000 m and tunnel length of 4 km. The risk represents the number of casualties per year. HGV: heavy goods vehicle, DGV: dangerous goods vehicle.

The main hazard scenario considered to be applicable for the two tunnel types is as follows: there is a traffic jam in tunnel followed by a collision at the tail of the traffic jam. Next a fire starts. Several fire types are taken into account depending on the vehicle type. In the tunnel ventilation is present and working. Hence the effect of fires is considered only downstream[1]. The event tree starting from a traffic intensity in the tunnel is shown in Figure 2.

The casualty model for a given fire is based on the following areas (lengths), see Figure 3):

1. a maximum area, $L_{max.effect}$, in which there is an effect of the fire;
2. an area near the exit, $L_{Plinear}$, in which the probability of a casualty increases linearly from zero to a value ($P_{casualty}$).
3. an area some distance away from the emergency exits in which the probability of a casualty is constant ($P_{casualty}$). The total length of this area is calculated by:

$$L_{total} = L_{max.effect} - \frac{L_{max.effect}}{d_{emer.exit}} L_{Plinear} \tag{3}$$

[1] downstream is the tunnel part between the incident and the exit of the tunnel

in which $d_{emer.exit}$ is the emergency exit distance. Note that the number of emergency exits in the effected area is designated by ratio of the $L_{max.effect}$ and $d_{emer.exit}$.

All three areas and the probability of a casualty depend on the specific fire type. The probability of casualties is assumed to be independent from the distance to the fire incident.

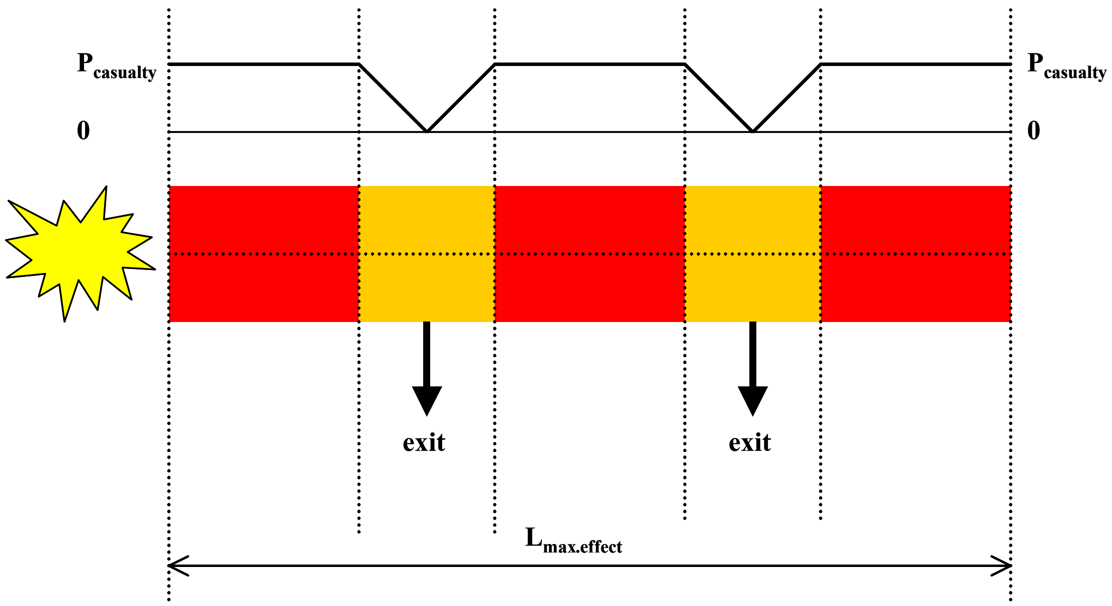

Figure 3 The probability of a casualty near and some distance away from the exits

Given the probability of casualties inside the areas near and away from the exit and the number of persons in these areas the expected number of casualties can be determined for each fire type.
Using the event tree (Figure 2) the frequency of each fire scenario per year per km tunnel length is calculated. By multiplying the frequency of each fire scenario with the number of casualties for each scenario the risk is found. By summing up the risks for each scenario the total risk is determined for the given tunnel for a given emergency distance. This result is also presented in the event tree in Figure 2.
Now the comparison of the risk add-on of casualties versus the constructions costs as a function of the emergency exit distance is made in terms of monetary units. The monetary value associated with a single casualty is taken equal to 3 M€ which is based on References 7 and 8. The risk add-on is considered over a period of 100 years and capitalised using a net discount rate of 3%. In Figure 4 the risk add-on of casualties is shown as a function of the exit distance. The risk add-on of casualties starts to increase very fast at small distances. But gradually the risk will hardly increase anymore. This is caused by the assumed model in which the number of casualties is inversely proportional to the emergency exit distance. Due to this model the optimum emergency exit distance is equal to the tunnel length, i.e. zero exits. This does not change if we increase the costs of a casualty. For the given set of tunnel characteristics and the main scenario there is no optimum emergency exit distance. This means that from an economic point of view the number of number of exits can be taken to be zero. Note that the risk add-on is almost fully determined by the fires due to the HGV's.

If we consider to have zero emergency exits in the bored tunnel, we have, of course, no additional constructions costs but we do have to take into account a risk add-on of 158 M€ in the integrated cost benefit analysis. If we consider to have emergency exits every 250 m (15 exits for a 4 km tunnel), we have to take into account 45 M€ construction costs (assuming 3 M€ per exit) and a risk add-on of 128 M€, see Figure 4. In that case we save only 15 M€ (= 45 + 128 – 158) by taking no emergency exits in the bored tunnel.

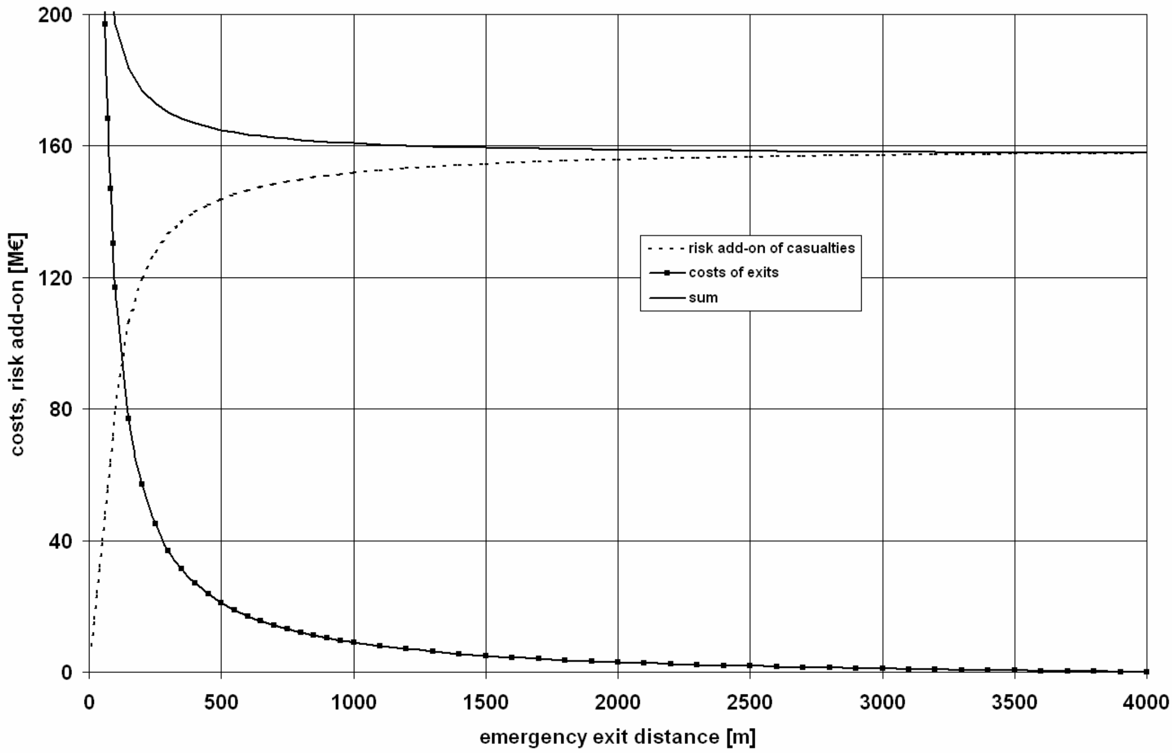

Figure 4 The costs of constructing emergency exits in a bored tunnel and the risk add-on (casualties) as a function of the emergency exit distance in the bored tunnel with a length of 4 km

5.3 Example 2: Emergency exits in a railway tunnel

Consider a bored railway tunnel with two tubes each having a single rail track. Also here the focus is on the emergency exit distance and its effect on the number of casualties. The example is presented in more detail in Reference 2, chapter 6. The casualty model is restricted to one main scenario: fire in a train in the tunnel. The model calculates the number of casualties caused by exposure to heat and toxic smoke in the tunnel. The model exists of four components:

- the fire model, dealing with the start and development of the fire;
- the model describing the (unwanted) stopping process of the train in the tunnel;
- the evacuation model for passengers after the train stops in the tunnel;
- the tunnel climate model: temperature, radiation, concentration of toxic combustion products as a function of time and distance to the fire.

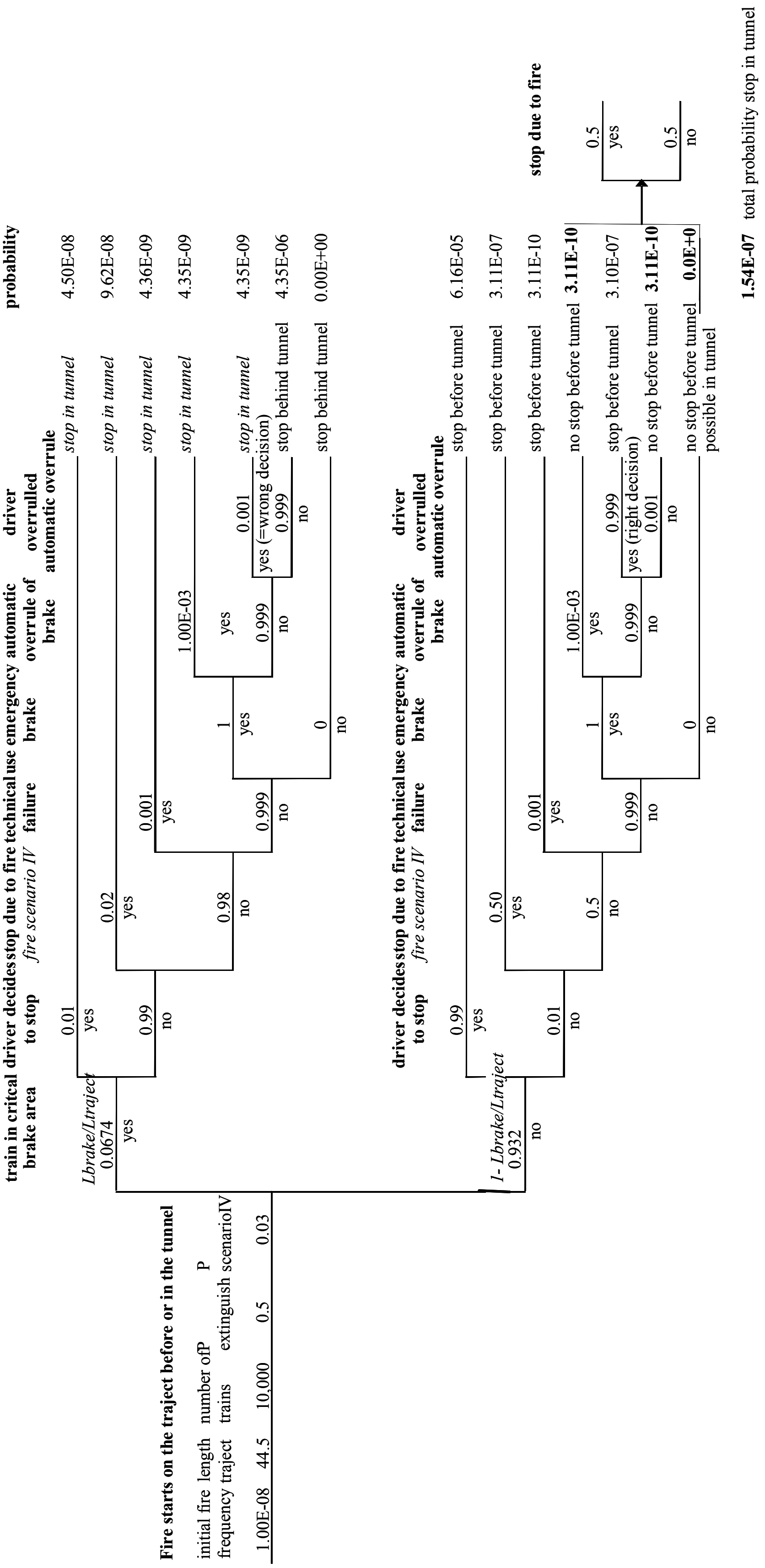

Figure 5 Event tree of a fire in a train tunnel including the results of railway tunnel with a length of 3 km [2].

The event tree of the fire scenario is given in Figure 5. The main elements of the model which have an influence on the consequences of a scenario are the number of trains passing through the tunnel per year, the number of passengers per train and the distance between the train exits and emergency exits.
When ventilation is available, the location of the fire in the train has an influence on the number of casualties. This is a result of the assumption that only the passengers which are downstream of the fire are exposed. In the model the location of the fire in the train is in the centre and the train is assumed to stopped between two emergency exits.
Although several fire scenarios can be considered, previous analyses showed that only one scenario is dominating the expected number of casualties, namely a fire with a flash over and a maximum heat release rate of 60 MW.
Figure 6 shows the risk add-on of casualties as a function emergency exit distance. Although the calculation of the casualties is more refined than for the road tunnel, e.g. the probability of a casualty depends on the distance to the fire, the risk add-on shows the same characteristics: again no optimum can be found. The constructions costs are not shown because these are much higher than the risk add-on of casualties. The risk add-on for the railway tunnel is much lower than the risk add-on for the road tunnel which caused by the higher fire frequencies.

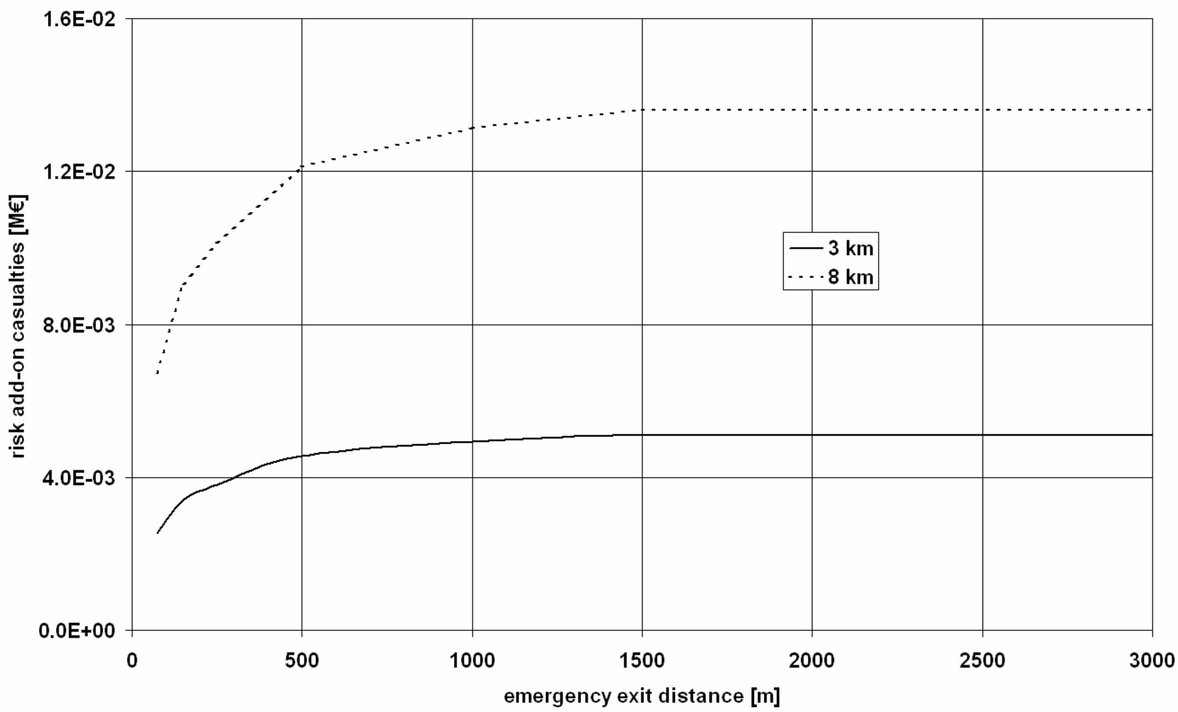

Figure 6 The risk add-on (casualties) as a function of the emergency exit distance in the bored railway tunnel with lengths of 3 and 8 km.

6. CONCLUSIONS

The DARTS project has shown that in principle design decisions with respect to various aspects can be taken on the basis of explicit cost optimisation criteria. This paper has shown that models are available to perform a hazard analysis for fire and to compute the consequences in terms of the number of casualties and money. This is a good basis for formulating procedures to find optimal integrated economic design solutions. The examples indicate that expensive emergency exits in bored tunnels may not be cost-effective. This result should be considered as premature and need confirmation in future studies. Essential is that the proposed systematic and rational method shows a new and refreshing light on important design decisions that until now were taken on intuitive and often highly emotional grounds.

7. REFERENCES

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Annex A

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- WP1: Process Management in the creation and operation of tunnels
- WP2: Reliability Based Service Life Aspects
- WP3: Environmental Aspects
- WP4: Hazards
- WP5: Integrated Design and Redesign (including life cycle cost optimisation)
- WP6: Benchmarking
- WP7: Exploitation and Dissemination

General information on the DARTS project, including links to the individual project partners, is available through the web site of the project on the Internet: http://www.dartsproject.net.