Bewertung der Sicherheit von Straßentunnel

Bericht in englischer Sprache

Assessing the safety of road tunnels

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Final Report

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Preamble

This final report describes the approach and the principles of the research project “Evaluation of the safety of road tunnels” (FE 03.378/2004FRB). The report documents a method for performing risk analyses according to the “Directive for the Equipment and Operation of Road Tunnels” (RABT 2006) or according to Article 13 of the Directive 2004/54EG of the European Commission concerning minimum requirements for the safety of tunnels in the trans-European road network as well as the principles and analyses required for deriving this method.

The main report documents the principles and the method with regard to the application of the method. Detailed information concerning the principles and the derivation is provided in the appendices to this report.

The work was performed between March 2005 and March 2007. It was coordinated by the Federal Institute for Highway Research and supported by a consulting committee.

Table of contents

List of figures

List of tables

List of abbreviations

Abbreviation	Explanation
A	Extent of damage
ADR	European agreement concerning the transport of hazardous goods on roads (Accord européen relatif au transport international des marchandises Dangereuses par Route)
DTV	Average daily traffic volume
CFD	Computational fluid dynamics
ESAS	Recommendations for safety audits of roads
ETA	Event Tree Analysis
F	Traffic accident
FIT	Fire In Tunnels
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GV	Two-way traffic (tunnel)
HAZOP	Hazard and Operability Analysis (risk-analysis method)
L	(Road) length
LP	Light personal injury
LV	Accident in the longitudinal traffic
MOZ	Mean local time
NFPA	National Fire Protection Association (USA)
OECD	Organisation for Economic Cooperation and Development
P	Personal injury
PHA	Preliminary Hazard Analysis (risk-analysis method)
PIARC	World Road Association
QRA	Quantitative risk analysis
RABT	Directive concerning the equipment and operation of road tunnels
RV	One-way traffic (tunnel)
S	Damage to goods
SO	Other accident
SP	Severe personal injury
StFV	Swiss Accident Ordinance
SV	Heavy traffic
t	Time
U	Accident
UD	Accident density
UKD	Accident cost density
UKR	Accident cost rate
UR	Accident rate
VUA	Traffic accident notification

Abbreviation	Explanation
W	Probability
WOZ	Actual local time
WU	Accident cost flat rate

1 Introduction and initial situation

Fires in various European road tunnels in recent years have highlighted the risks that tunnel users are exposed to when a vehicle catches fire. Appropriate safety systems and devices attempt to counteract the additional risk potential that tunnels pose in addition to the risks on open roads.

The European Union (EU) provides a regulatory framework concerning the minimum safety requirements for tunnels in the Directive 204/54/EG [1] in order to achieve the highest possible standardisation of safety-relevant installations in European tunnels. According to Article 13, it requires explicit proof of the effectiveness of individual safety measures by risk analyses.[1] The German Directive for the Equipment and Operation of Road Tunnels (RABT 2006) [2] has incorporated and amended these specifications for the use of risk analyses [1].

However, neither of the two directives provides any further information on the methodical requirements for risk analyses. Instead, the EG Directive requires its member states to develop a suitable method for the evaluation of the safety of road tunnels at a national level. This report documents the method developed as part of the research project “Evaluation of the safety of road tunnels” (FE 03.378/2004FRB) at the request of the Federal Highway Research Institute (BASt) as well as the relevant principles and analyses.

The suggested method is also used as basis for a report concerning the practical application in member states, which needs to be compiled by the EU Commission until 30 April 2009. The EU intends to develop subsequently a suggestion for determining common, harmonised methods for risk analyses.

2 Goals and delimitation

2.1 Goal for the research project

The goal for this research project was the development of a method for evaluating the safety of road tunnels and of the appropriate principles for applying it as part of the implementation of the EC Directive or the RABT 2006. This involved the following targets:

- Provide an overview of the current state of the safety evaluation of road tunnels as well as the principles for procedures and methods for safety evaluation.
- Create a standardised set of basic data or a definition of the structure required for future data collection efforts to facilitate safety evaluations for road tunnels.

[1] The EC Directive [1] discriminates between risks according to Article 13 and risk analyses, which are not specified in detail. An appropriate overview is provided in Appendix 1.

- Show the systematic connections and interactions with regard to risk-relevant factors for road tunnels.
- Develop a standardised method for evaluating the safety of road tunnels based on quantitative risk analyses.

2.2 Delimitation

The method developed in this research project is mainly based on the two damage indicators: personal injuries and damage to goods. Further aspects such as the availability of road tunnels or possible down-times after accidents and resulting losses to the national economy are implicitly considered by the method, but they are not separately presented.

3 Procedure for evaluating the safety of road tunnels

3.1 Risk-oriented safety evaluation

A systematic safety evaluation based on a risk-oriented approach consists of several individual steps that can be grouped into three main areas as shown in Figure 1 below.[2]

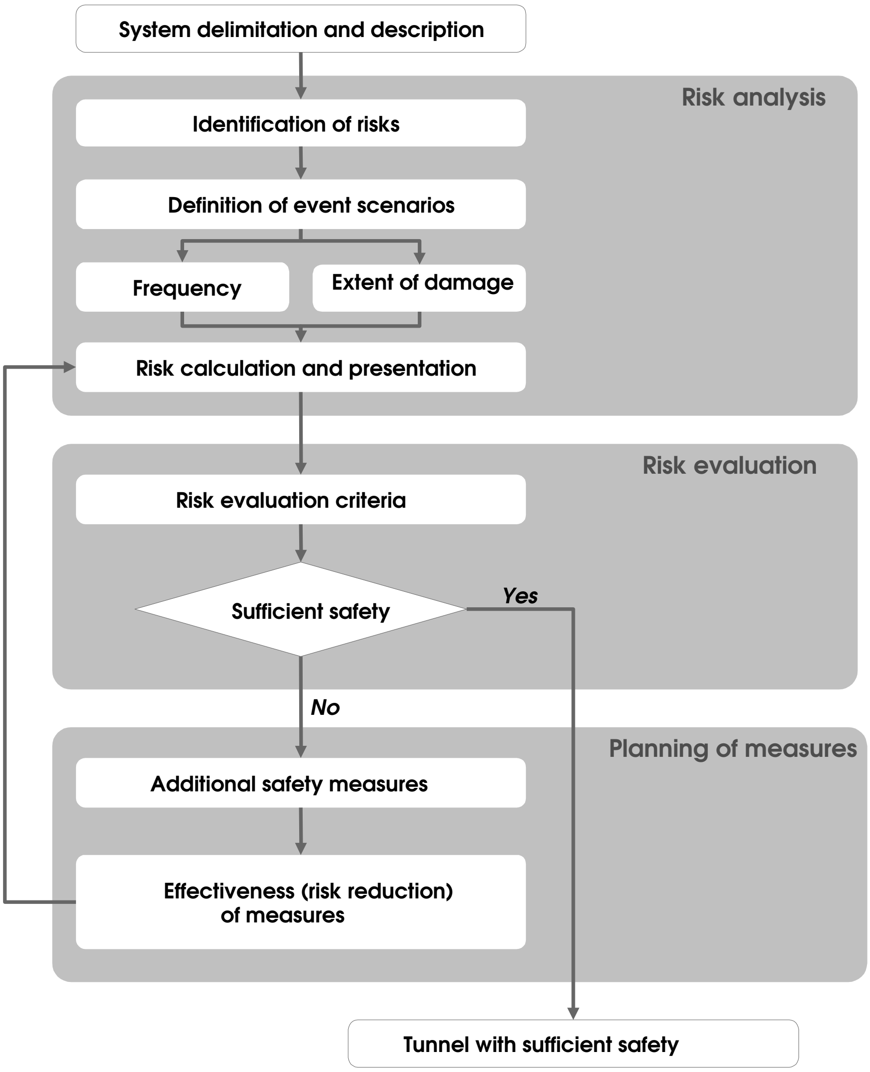

Figure 1: Elements of the risk-oriented safety evaluation

- *Risk analysis:* The risk analysis is the basis of safety evaluation. Risks are identified and the expected frequencies and the extent of damage for the events are (quantitatively) estimated. In simple terms, risk analysis is an attempt to answer the question "What can happen?"

[2] It should be noted that no standardised terminology has been established at an international level or within the various specialist areas. The terms used in this research project are explained in the glossary.

- *Risk evaluation:* The risk evaluation includes concepts concerning the acceptance of the damage and the readiness to use means to prevent it. The evaluation cannot be derived in an objective manner and depends on the decisions of the parties involved. Risk evaluation includes an assessment of whether the safety level of a system is sufficient. In simple terms, risk evaluation is an attempt to answer the question "What do we allow to happen?"
- *Planning of measures:* Measures are planned in several steps from the selection of risk-reducing measures to the evaluation of these measures with regard to their effectiveness for risk reduction and their costs. The planning of measures should provide an answer to the question "Which measures are required to make the system safe?" The results of the planning of the measures are again used as input into the risk analysis and risk evaluation.

3.2 Requirements and principles

3.2.1 Regulatory framework for the safety of road tunnels

After the fires in the Mont Blanc (F/I) and the Tauern (A) road tunnels, considerable efforts were made in numerous European states as well as at an international level to improve the safety of road tunnels. Numerous adaptations and amendments based on the findings in the two accident events were particularly made in the area of regulations (standards and directives).

In 2004, a new directive concerning the minimum requirements for safety of road tunnels of the trans-European road network was passed on the European level and numerous research projects were conducted. The EC directive as well as the RABT 2006 require clearly defined, technical and constructive measures according to the state of the art (measures-oriented approach). They also mention requirements or the option of using safety measures that are provided in accordance with the specific risk situation at a tunnel (risk-oriented approach).[3] Requirements concerning the implementation of a risk-oriented evaluation are only mentioned in connection with specific points.

In the past, requirements concerning safety measures in road tunnels were mainly based on a measures-oriented approach. Risk-oriented considerations were only applied in some individual cases. A literature study investigated the various international basic regulations (standards, directives) for possible risk-oriented approaches and possible specifications concerning methods.

The following basic regulations were evaluated:

Country	Title
Germany	• Directives for equipping and operating road tunnels (RABT 2003) [2]

[3] Further information concerning the differentiation between these two approaches is provided in Chapter 3.2.2

Country	Title
France	• Circulaire interministérielle n°2000-63 [4] • Circulaire interministérielle n°2000-82 [5] • Guide des dossiers de sécurité des tunnels routiers, fascicule 4 [6]
UK	• BD 78/99 Design of Road Tunnels [7]
Austria	• RVS 9.234 Project planning directives, internal construction [8] • RVS 9.261 Project planning directives, ventilation systems, principles [9] • RVS 9.281 Project planning directives, operating and safety devices, building structures [10] • RVS 9.282 Project planning directives, operating and safety installations, tunnel equipment [11]
Switzerland	• SIA 197 Project planning for tunnels - principles [12] • SIA 197/2 Project planning for tunnels - Road tunnel [13] • ASTRA, Signalisation of safety devices in tunnels [14] • ASTRA, Ventilation of road tunnels [15]
USA	• NFPA 502, Standards for road tunnels, bridges and other limited access highways [28]

Table 1: Basic regulations evaluated

The situation in the following countries was investigated, but no detailed investigation of the standards was performed:

- Norway
- Japan
- Netherlands

The evaluation of the requirements for safety measures in the regulations investigated shows that measures-oriented approaches are used in most cases. Risk-oriented approaches are sometimes included through risk-relevant factors such as traffic volume or tunnel length, which may co-determine the requirements for safety measures. The results are then used to derive the standards for the specific measures that have to be provided (grouped by class). However, the risk-oriented approaches mentioned in the basic regulations investigated cannot be interpreted as an actual risk analysis

Some states have developed approaches for safety evaluations with risk analyses, but the relevant methodical foundations have not yet found their way into the relevant standards and directives.

It was found with regard to the key questions for this research project that the basic standards evaluated contain some references to requests for risk-oriented considerations or risk analyses, but that specific, methodical requirements or assistance are only provided in rare cases. Where information is provided, it usually concerns pragmatic estimates (e.g. Austria, UK) with simple formulae or similar tools or references to detailed studies (e.g. OECD/PIARC [16]). It was furthermore found that risk-oriented approaches are usually mentioned or required in connection with relatively rare, major events such as fires in tunnels or release of hazardous substances.

Additional information concerning these evaluations is provided in Appendix 1.

3.2.2 Basic method for the safety of road tunnels

3.2.2.1 Approaches to safety evaluation

Three basic approaches for safety evaluation can be identified [19]. Practical applications often involve combinations:

- *Empirical approach:* The empirical approach is mainly based on the principle of "trial and error". The development of a safe system proceeds more or less naturally, based on the ongoing experience during the uses. The findings derived from faults, disturbances or accidents are used as a basis for implementing new safety measures. Accidents play a special role, as they are reoccurring events that trigger important developments and the appropriate efforts for improving safety. The empirical approach is appropriate where relatively frequent events with small extent of damage provide the necessary experience for improvement.
- *Measures-oriented approach:* While the measures taken with the empirical approach are those that seemed necessary due to experience, the measures-oriented approach focuses on the total range of available safety measures and the measures that need to be implemented. The goal is to use the appropriate measures to make a system, e.g. a road tunnel, sufficiently safe before accident events create pressure for appropriate measures. The measures-oriented approach compares a system with the state of the art, defined specifications or standards. Specific characteristics[4] of the system have no or only marginal relevance. The appropriate measures are taken independently according to the state of the art.
- *Risk-oriented approach:* The risk-oriented approach plans safety measures according to the risks determined for the system investigated and the explicit evaluation of these risks. Safety is proven according to one or several risk indicators that are measured against predefined reference values. The risk-oriented approach is preferably used for new and/or complex questions.

[4] It is, for example, not considered that a tunnel can have high or low traffic volume and that the expected frequency of an accident or fire can vary.

The currently required safety measures for road tunnels are mainly based on the measures-oriented approach, which is oriented towards the current state of the (safety) technology. This approach is not sufficient for the risk analysis required in the EG directive [1], as the complexity of the system and the interactions between the constructive and technical safety measures is too high. For such purposes, a risk-oriented approach is required.

3.2.2.2 Overview of methods

The safety of road tunnels can be evaluated with qualitative and quantitative methods.

The qualitative methods are based on the use of arbitrarily definable evaluation scales. It poses the risk that impact of subjective impressions is too high and that the systemic interactions between individual measures/components are not fully considered. This may, for example, lead to the conclusion that a higher number of safety measures leads to a proportional increase in safety. These methods also do not allow any comparisons, e.g. between the risks of road tunnels and risk in other traffic areas.

The quantitative methods attempt to map event sequences in the system “road tunnel” in a logical and structured manner. Possible event sequences are simulated, starting with an initial event. The factors that affect the development of a specific event sequence are identified and their impact is investigated. The results are used to determine the accident frequencies and the level of damage for the various, scenario-specific event chains in order to determine the appropriate risk.

A major advantage of the quantitative methods is a transparent presentation of the calculations from the initial event to the subsequent events and the final state, which provides a better understanding of complex interactions.[5]

The elements of the basic methods that can in principle be used for a safety evaluation are shown in a graphical overview in Figure 2. The method elements are grouped into three areas that correspond to the main steps required for a safety evaluation: Risk analysis, risk evaluation and planning of measures (see Chapter 3.1):

- *Risk analysis:* The method elements can be seen as tools that can be combined for the risk analysis. This is often required in practical applications to fill gaps in the available data.
- *Risk evaluation:* Usually, evaluation methods can only be combined to a limited extent.
- *Planning of measures:* The selection of the method for the planning of measures is closely related to the evaluation method used.

When the method elements from risk analysis, risk evaluation and planning of measures are combined, a total method is created. However, the elements cannot be freely combined. Certain

[5] *"Quantification does not establish truth, but those who avoid it shy away from facing a ‘truth’ that can at least be criticised." (Robert Fogel, Nobel Price winner for economics)*

evaluation methods require certain analysis methods and the evaluation of measures is closely linked to the evaluation methods.

Further information concerning the method elements is provided in [19] as well as in an investigation that was conducted as part of the European research project SafeT [20]. Additional information concerning the most important method elements as well as experience with the use of qualitative and quantitative methods are summarised in the Appendices 2 and 3, which also contain the principles for computer-based methods.

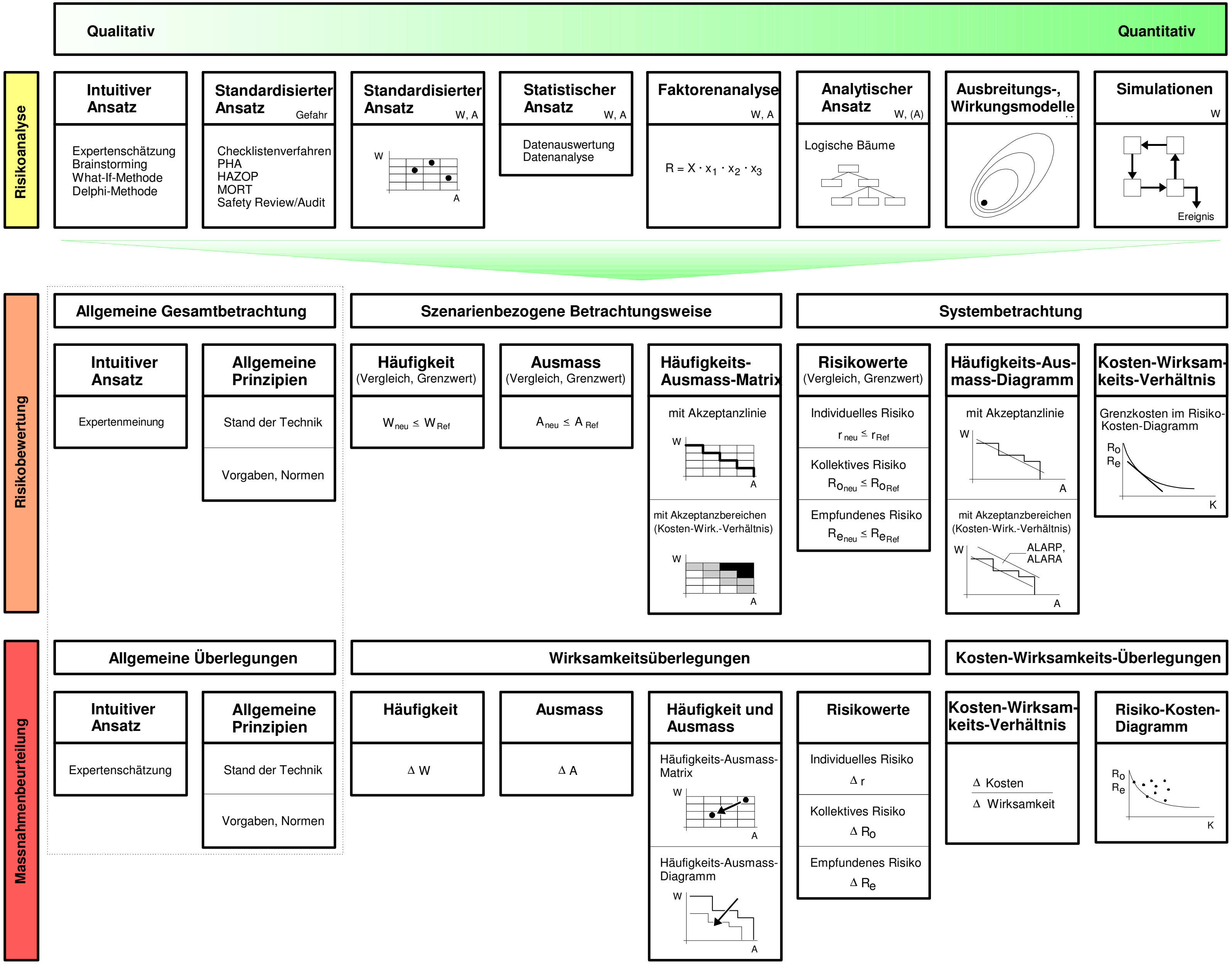

Figure 2: Overview of common analysis and evaluation methods

3.2.2.3 Requirements for methods in 2004/54/EC and RABT 2006

The directives of the EC [1] and the RABT 2006 do not provide detailed specifications concerning methodical requirements for safety evaluation. However, two main thrusts can be derived from the contents of both directives:

- *Proof of equivalent safety:* The EC directive specifies the minimum requirements for the structure and equipment of road tunnels. If a tunnel complies with these requirements, the directive is considered as having been complied with and no further safety considerations are required. If not all requirements can be implemented according to the directive, e.g. for cost reasons or when the use of new technologies is planned, alternative safety measures must be provided. These must be capable of achieving at least the same level of safety. A safety certificate must show that the required safety level is achieved or exceeded in spite of a deviation from the specifications of the directive.
- *Cost-effectiveness:* If the safety certificate shows that the deviation from the specifications of the directive requires additional safety measures, the aspect of cost-effectiveness has to be considered to ensure that the effort required is in proportion to the benefits.

3.2.3 Requirements for methods

The following requirements for methods are stipulated as a result of the evaluation of the regulatory and methodical basis:

- The method should consider the important, risk-relevant factors for risk analysis according to Article 13 of the Directive 2004/54/EC [1] or the RABT 2006 [2].
- The method should be based on quantitative analysis.
- The method should consider the methodical approaches developed in other states according to the requirements of the Directive 2004/54/EC [1], as far as this is considered as useful.
- The damage indicators used by the method should be based on the approach common in risk analyses. Therefore, the following two damage indicators are used:
  - Personal injuries [fatalities][6]
  - Damage to goods and to persons [€]

[6] Injured persons are allocated to the damage indicator "damage to goods" by adding the appropriate accident costs.

3.3 Relevant event scenarios

3.3.1 Introduction

The risk-oriented safety evaluation of road tunnels is in principle based on the three elements of risk analysis, risk evaluation and planning of measures that are described in Chapter 3.1. This chapter deals with the relevant aspects for determining the most important event scenarios.

3.3.2 Risk identification / risk analysis

Experience shows that the spectrum of possible accident and event sequences in road tunnels and the resulting possible injuries and damage to goods can be considerable. It depends on tunnel-specific characteristics such as the constructive details, the presence and nature of safety measures and situation-specific characteristics such as the type of the vehicles involved or the behaviour of the traffic participants, etc.

The first step of a safety evaluation therefore involves mapping and structuring the risks relevant for the issue under investigation and the resulting event scenarios. The following matrix (Figure 3) summarises the results and provides an overview of possible event sequences. The matrix also provides a structured overview of the spectrum of possible event scenarios and indicates possible options/degrees of severity based on sample descriptions. Additional information concerning the scenario types and possible event sequences is provided in Appendix 4.

Figure 3: Overview of possible event scenarios in tunnels

Sz.	Ereignis-kategorie	Involvierte Fahrzeuge bzw. Substanzen/Objekte	Schweregrad 1	Schweregrad 2	Schweregrad 3	Schweregrad 4
1	Panne	Pkw	Panne in Pannenbucht	Panne am Fahrbahnrand	Panne in der eigenen Fahrbahn	Panne, bei der beide Fahrbahnen tangiert sind.
2		Lkw				
3		Reisebus				
4	Kollision (ohne Brand)	Pkw	Kollision mit Tunnelwand	Auffahrkollision	Streif- und Frontalkollision	Schwere Frontalkollision
5		Lkw				
6		Reisebus				
7		Massenkollision	Leichte Auffahrkollision	Schwere Auffahrkollision	Frontal- und Auffahrkollisionen	Schwere Frontal- und Auffahrkollision
8	Brand (ohne Gefahrgüter gemäss ADR)	Pkw Panne / Kollision	Motorenbrände bzw. kleine und einfach kontrollierbare Brände	Fahrzeugbrände bzw. mittlere und eher schwer kontrollierbare Brände	Grosse und schwer kontrollierbare Brände z.B. nach Kollisionen. Grosse Behinderung durch Rauchentwicklung.	Unkontrollierbare Brände, die sich auf zahlreiche andere Fahrzeuge übertragen. Rauch mit giftige Gasen vermischt.
9		Lkw Panne / Kollision				
10		Reisebus Panne / Kollision				
11		Massenkollision (Pkw, Lkw, Reisebus)				
12	Ereignisse mit Beteiligung oder Freisetzung von Gefahrgütern gemäss ADR	Feste Stoffe (Explosivstoffe)	Brand der Verpackung	Abbrand	Brand / Deflagration	Explosion
13		Leichtentzündliche Flüssigkeit (Benzin)	Kleines Leck bei Durchfahrt	Lache ohne Zündung	Lache mit Zündung	Bersten des Tankes, Grossbrand
14		Brennbares Gas (Propan)		Leck ohne Zündung	Freistrahlbrand	Unterfeuerung (BLEVE)
15		Humantoxisches Gas (Chlor)		Mittleres Leck	Grösseres Leck	Grosses Leck, sofortiger Ladungsverlust
16		Ökotoxische Flüssigkeit (Acrylnitril)				
17		Radioaktive Substanz	Kollision ohne Strahlungsfreisetzung	Leichte Strahlungsfreisetzung im Fahrzeug	Mittlere Strahlungsfreisetzung im und um Fahrzeug	Schwere Strahlungsfreisetzung im Fahrraum
18	Wirkungen von ausserhalb des Tunnels	Gegenstände / Stoffe	Witterungseinflüsse (Nebel, Starkniederschläge, Sturm etc.)	Brand ausserhalb des Tunnels mit Rauchgasausbreitung in den Tunnel	Explosion / Freisetzung toxischer Gase ausserhalb Tunnel	Überflutung des Tunnels

3.3.3 Essential event scenarios

Five simplified scenario types can be distinguished, based on the structure in Figure 3:

- *Scenario type "Breakdown":* Usually, breakdowns do not lead to severe injuries or damage to goods. The main aspects are obstruction or interruption of the operation. In a security context, breakdown scenarios are mainly relevant as possible causes for subsequent events such as collisions or fires.
- *Scenario type "Collision (without fire)":* It can be expected that the severity of injuries and damage to goods will depend on the particularities and the type of accident. Collisions can be classified into accidents without third parties (e.g. collision with the tunnel infrastructure) and accidents with other vehicles. Also this scenario type can be a trigger for subsequent events such as collisions or fires.
- *Scenario type "Fire (without hazardous goods according to the ADR[7])":* Fires in road tunnels in recent years have led to numerous innovations and adaptations of the standards for safety measures. This scenario type is therefore particularly relevant for safety measures, as a large part of the safety measures requested in standards and directives target this type of scenario (fire ventilation, fire detection, etc.). Also in such cases, the severity of the resulting damage will depend on the burning object and the particularities of the event.
- *Scenario type "Events with involvement or release of hazardous goods according to the ADR":* Events involving the release of hazardous goods in road tunnels are very rare, but can potentially cause considerable damage. Depending on the type of the hazardous good released, different types of effects such as fires, explosions or toxic effects are possible.
- *Scenario type "Effects from outside the tunnel":* Also effects from outside a road tunnel can have a safety-relevant impact. In addition to weather effects such as strong rain, storm or fog, also natural disasters (flood, earthquake, etc.) or other effects such as explosions or spreading of smoke or toxic gasses must be considered. Usually, this type of event is very rare or the effects in the area of the tunnel are very small.

From a safety point of view, the scenario types “Breakdown" and “Effects from outside the tunnel” are of minor importance when compared to the other scenarios and are therefore not considered for the method for the following reasons:

- The main damage effect for the scenario type “Breakdown” is the interruption of operations, which is strictly not a safety-relevant aspect. In addition, the planning of measures to reduce these risks with breakdown lanes and breakdown bays can only draw on a very limited

[7] European agreement concerning the transport of hazardous goods on roads (Accord européen relatif au transport international des marchandises Dangereuses par Route)

spectrum of options. In the method developed, this scenario type is therefore mainly considered as a cause for subsequent events.

- Scenarios of the type “Effects from outside the tunnel” are usually very rare or their effect in the tunnel is very limited. The range of possible safety provisions is generally also very limited.

The method for safety evaluation with regard to the question at hand therefore mainly considers the following three scenario types:

- Scenario type "Collision (without fire)"
- Scenario type "Fire (without hazardous goods according to the ADR)"
- Scenario type "Events involving or releasing hazardous goods according to the ADR"

It is by now common practice for hazardous goods risk analyses (scenario type “Events with the involvement or release of hazardous goods according to the ADR”) to investigate not only one tunnel, but to compare the risks of one tunnel route with those of a possible alternative route. The computer model OECD/PIARC [16] is available for safety evaluations for this scenario type. It allows the comparison of the risks for the transport of hazardous goods through a route with tunnels with the risks for the transport on a possible detour. The model includes a total of 13 release scenarios and is already used in several countries (e.g. UK, Austria, and France).

The use of the OECD/PIARC model requires considerable effort and the part for estimating the extent of damage has only limited capabilities for mapping the tunnel characteristics and in particular small-scale effects of hazardous goods. However, the model seems to develop towards a standard for the risks of hazardous goods. It is therefore recommended to use the OECD/PIARC model or equivalent models for risk analysis concerning transports of hazardous goods through road tunnels as required by the Directives 2004/54/EG and RABT 2006.[8] This issue was therefore not considered in more detail within this research project.

[8] Equivalent models and experiences for the evaluation of safety of hazardous goods transports through road tunnels also exist in Germany (e.g. for the tunnel chain on the federal motorway A71 in the Thüringer Wald with the Rennsteig Tunnel I).

4 Application of the method for the evaluation of safety in road tunnels

This chapter shows the proposed procedure for safety evaluation of road tunnels and explains the relevant method elements. The focus is on the application of the method. Additional information concerning the derivation of the method elements and the evaluated basic regulations is provided in the appropriate appendices.

4.1 Risk analysis

4.1.1 General aspects of the procedures

It has been stipulated that all tunnels with a length of at least 400 m must be equipped or planned and operated according to the specifications of the RABT 2006. A tunnel that complies with the requirements of the RABT 2006 is considered safe.

- If a tunnel does not comply with the valid specifications with regard to design, safety measures or other aspects, the resulting risks are determined, using an event-tree analysis (see Chapter 4.1.2) of the two scenario types "Collision (without fire)" and "Fire without hazardous goods according to ADR" as follows:
  a) Determine the risk situation for the tunnel to be investigated (initial state)
  b) Determine the risk situation for the tunnel to be investigated, assuming that all specifications have been adhered to (reference state)
  c) If required as a result of the risks for a) and b), the risks for the tunnel to be investigated are determined assuming alternative safety measures.
- The risks for each tunnel section are separately determined and aggregated to a total evaluation to ensure high flexibility of the method with regard to its application to different tunnel types. This way, specific differences between individual tunnel sections of a tunnel, for example different tunnel geometry, can be taken into account.
- The risks for the two scenario types mentioned above are separately determined. This approach shows the importance of the different scenario types with regard to the resulting total risk and the impact of specific safety measures on each scenario type.
- The scenario types are delimited by always considering the most relevant scenario type (worst case), e.g. a fire that results from a collision (or breakdown) is allocated to the scenario type "Fire" and not the scenario type "Collision". This is particularly relevant for estimating initial frequencies[9]. It ensures that scenarios that do not cause significant damage but might lead to damage due to possible, consecutive events are also considered in the safety evaluation.

[9] Initial frequency is the frequency with which a specific trigger event (in this context a fire) occurs.

- The damage indicator "fatalities" is used for determining damage to persons, as is common in comparable risk studies. Damage to goods is quantified in Euro. The "Damage to goods" also includes the consequential costs for injured persons under the consequential costs of accidents. The method provides additional options for combining the two damage indicators by using a comparable, monetary basis.
- The use of safety measures as part of the safety evaluation focuses on constructive and technical measures (in particular escape routes and ventilation systems). However, the method suggested can also be used to consider organisational and operational measures.

4.1.2 Event tree analysis and risk characteristics

A central component of risk analysis is based on event-tree or event-sequence analysis. Event-tree analysis is used to structure and analyse event sequences that develop from a specified initial event. This is an inductive analysis that starts with an initial event and determines possible, subsequent events with regard to their probability of occurrence and the resulting consequences (forward-directed logic). The consequences caused in a system by an initial event are step-by-step tracked to the final state of the system. Each event in this chain considers the consequences of the previous events. A simple graphical representation (the event tree, see Figure 4) can be used to map and calculate these logical sequences by using the conditional probabilities that the sub-systems involved function or fail in a specific sequence or that a specific condition occurs or does not occur. Each branch of the event tree represents a possible link from the initial event to possible consequential events.[10]

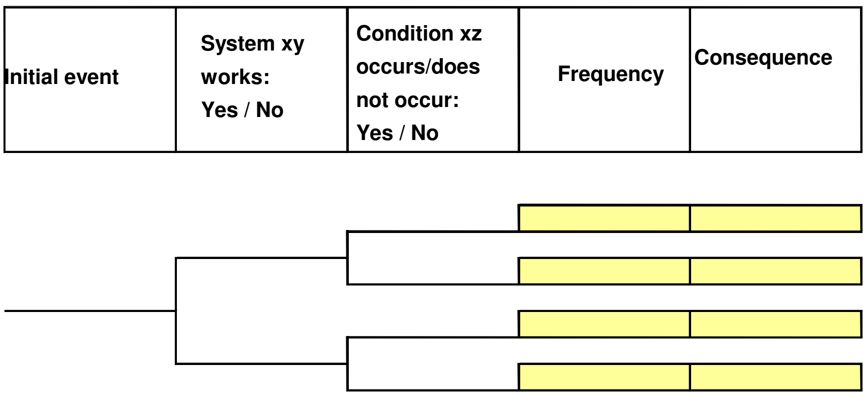

Figure 4: Example of a graphical representation of an event tree analysis

The associated, collective risk R_{ij} can be calculated from the frequency of an initial event H_i, the conditional event probability W_{ij} that certain subsystems activated in sequence work or fail or

[10] Theoretically, the event-tree analysis always considers two branches, according to binary logic (e.g. "works / does not work"). In practical applications, it is common to use several branches at one node of the event tree to map several system states with a single node in the event tree and to limit the complexity and size of the event tree.

that a specific circumstance occurs or does not occur and the resulting extent of damage A_{ij} of an event sequence j:

$$R_{ij} = H_i \cdot W_{ij} \cdot A_{ij}$$

In the long term, the collective risk is equal the mean extent of damage and therefore represents the expected amount of loss.

In addition to determining collective risks, the event tree analysis can also be represented in a damage frequency diagram: The addition of the frequencies

$$H_{ij} = H_i \cdot W_{ij}$$

over all event scenarios with an amount of loss equal or larger than a specified value can be used to determine the cumulative frequency for any extent of damage. The graphical representation of this cumulative frequency distribution in a double-logarithmic damage frequency diagram corresponds to the cumulative curve. It can be presented for individual scenario types and for the resulting overall risks (see example in Figure 5). The collective risk corresponds to the area under the cumulative curve in the damage frequency diagram.

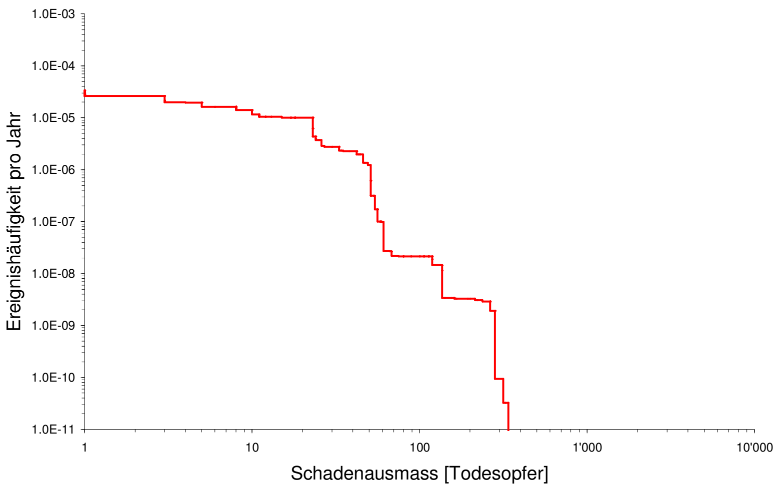

Figure 5: Example for damage frequency diagram with cumulative curve

The structure of the event trees used for this method is kept as simple as possible to provide a better overview and make the application easier. The effect of important factors such as tunnel-specific characteristics or the traffic volume is taken into account when determining the frequencies and the conditional probabilities in the event tree. The risk-relevant factors are expressed by categorical values as far as this is possible to make the selection of the conditional probabilities as easy as possible for the user. This basic approach is illustrated in Figure 6.

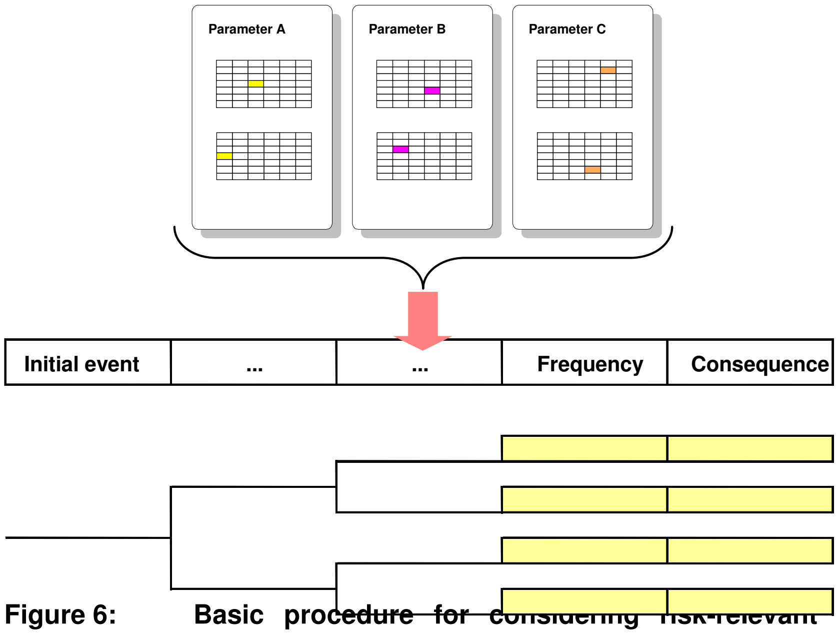

Figure 6: Basic procedure for considering risk-relevant factors with probability tables (above) in an event tree (bottom)

This method structures the risk-relevant factors in a specific manner, partially in table form. The conditional probabilities are determined by selecting the relevant factors and adapting them with adjustment factors to fit the tunnel under investigation.

The evaluation of the cost efficiency of measures as requested in the directives 2004/54/EG and RABT 2006 requires that the risks be expressed in monetary values and then compared with the costs of the measures. The required procedure is described below.

4.2 Scenario type “Collision

4.2.1 Scenario definition

The scenario type “Collision (without fire)” includes the following sub-scenarios:

- Road accident (Accident Type 1 according to [30]; accident without a third party, e.g. collision with tunnel infrastructure)
- Turning/crossing accident (Accident Type 3 according to [30], collision at exit / feeder road in the tunnel)
- Accident in longitudinal traffic (Accident Type 6 according to [30], e.g. rear-end collision or collision after a change of track in a one-way-traffic tunnel)
- Other accident (Accident type 7 according to [30]; e.g. collision with an object, sudden physical incapacity, failure of the vehicle)

Additional, illustrated explanations concerning possible event sequences and scenarios are provided in Appendix 4. A summary of accident types and sub-types is provided in Appendix 6.

4.2.2 Event tree

Figure 7 and Figure 8 show the structure of event trees for the scenario type “Collision” (for the damage indicators “Fatalities” and “Damage to goods/injuries”). The section shows the branching points in the event tree and the elements for the calculation of the extent (incl. the monetarised risks), which are individually numbered from 1 to 10. The complete event trees for the two damage indicators considered are provided in Appendix 5.

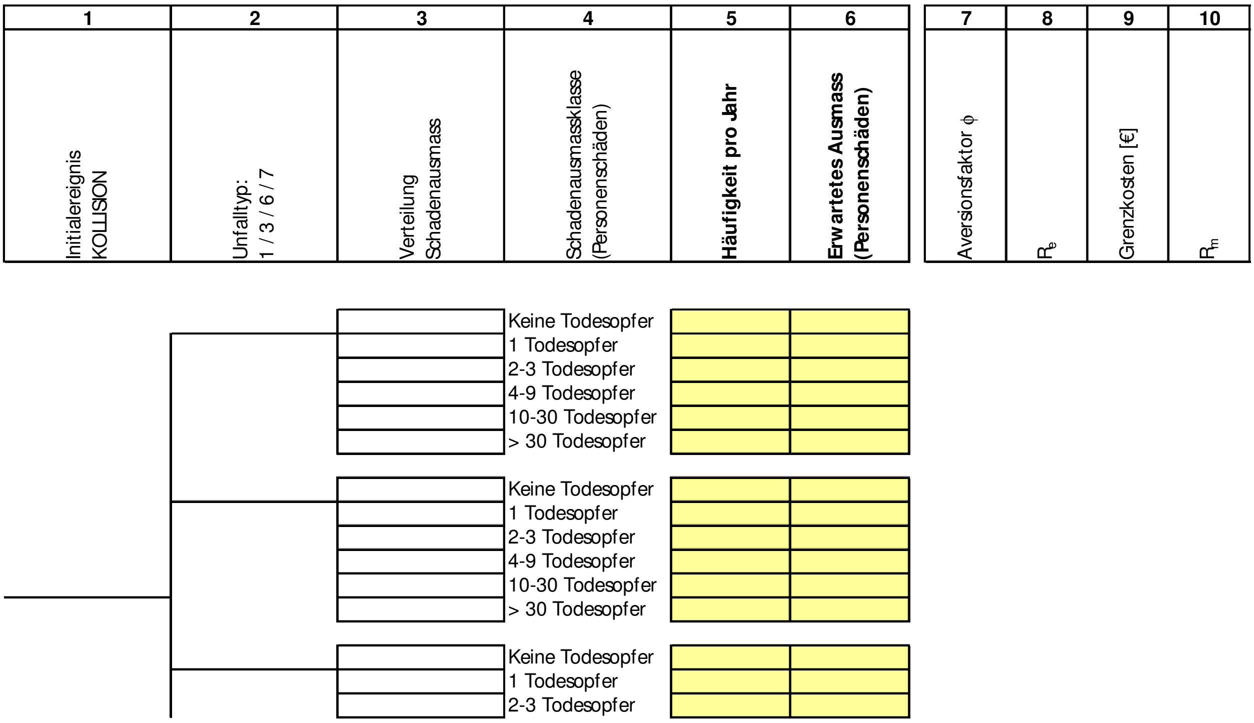

Figure 7: Structure of the event tree for scenario type “Collision (without fire)” for the damage indicator “Fatalities”

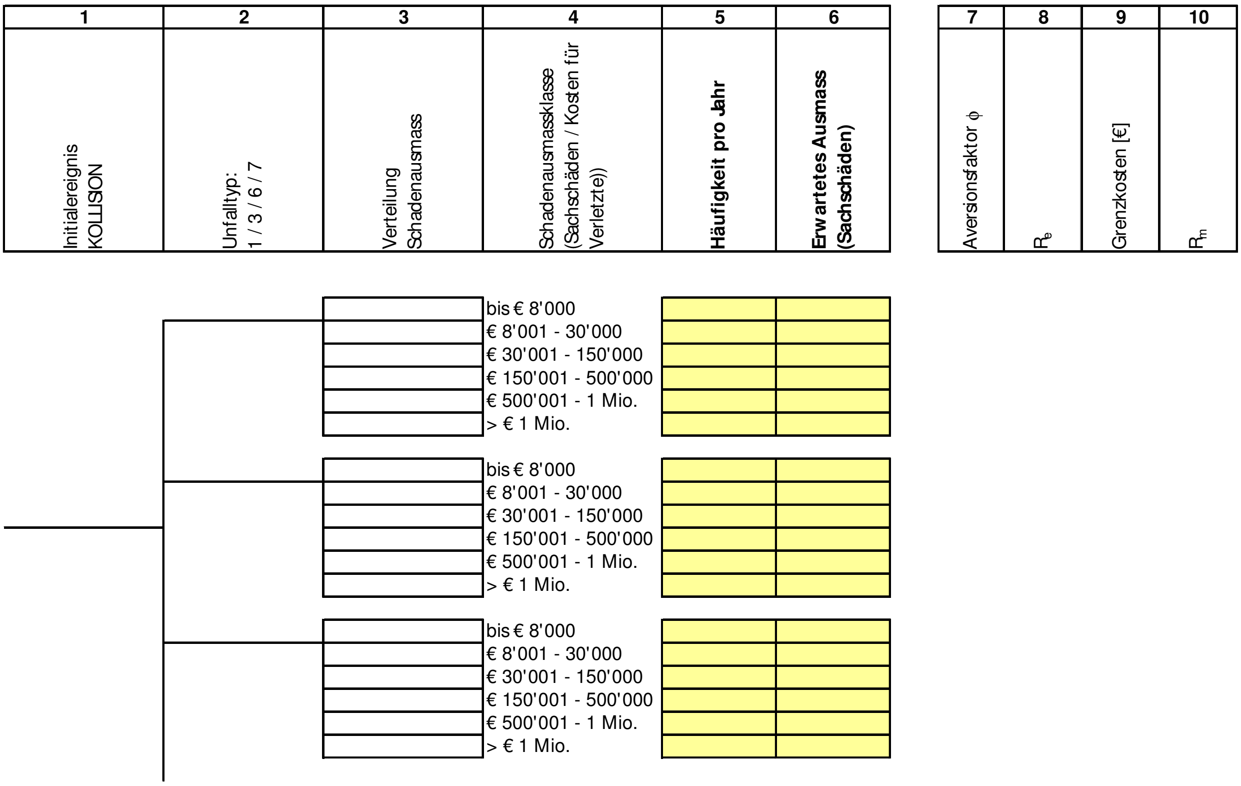

Figure 8: Structure of the event tree for scenario type "Collision (without fire) for "Damage to goods and injuries"

The factors for determining the frequencies/probabilities and the resulting extent of damage as well as the required processing steps for the calculation of the risks due to a collision are explained below. The processing steps are structured according to the branching points of the event tree.

4.2.3 Event frequencies, extents of damage and resulting collision risks

Branching point 1: Frequency of the initial event "Collision"

The frequency of the initial event is the collision frequency that can be expected for a specific tunnel or tunnel section. Based on an extensive evaluation of a total of 979 accident events in 80 tunnels in Germany, the statistical key values for determining the collision frequencies were determined as a function of the tunnel characteristics. The following factors were identified as relevant:

- Tunnel type / traffic type
- Tunnel length
- Traffic volume (DTV)
- Tunnel with or without feeder and exit roads

The following formulae as well as Table 2 have to be used to determine the annual frequency of a collision in a specific tunnel. The initial frequency of a collision in a tunnel segment can be determined with the following formula:

$$H_{Kol} = \alpha \cdot L \cdot DTV_{Röhre} \cdot 365$$

H_{Col}: Frequency of a collision in the tunnel segment considered [1/year]

α: Statistically corrected accident rate [1/(vehicle*km)]

$DTV_{Segment}$: Average daily traffic load per tunnel segment [vehicles/day]

L: Length of the tunnel segment under investigation [km]

Tunnel type	**Tunnel with feeder/exit roads**	**Tunnel without feeder/exit roads**
One-way-traffic tunnel	$5.28 * 10^{-7}$ [1/(vehicle*km)]	$2.28 * 10^{-7}$ [1/(vehicle*km)]
Two-way-traffic tunnel	$9.81 * 10^{-7}$ [1/(vehicle*km)]	$6.81 * 10^{-7}$ [1/(vehicle*km)]

Table 2: Corrected accident rate α for estimating the collision frequency (according to Appendix 7)

The following must be considered for applications to two-way-traffic tunnels: If only one of the two driving directions in the tunnel has a feeder/exit road, the resulting collision frequency must be determined through proportional allocation of the DTV.[11]

A mean collision rate of $6 * 10^{-7}$ [1/(vehicle*km)] can be derived from the accident analysis. The estimate according to the above formula also considers that collisions can result from breakdowns (e.g. rear-end collision with a broken-down vehicle).

The frequency of a collision can also be affected by factors such as:

[11] Example: Two-way-traffic tunnel with 3 lanes, due to uneven traffic loads (1 in Direction A, 2 in Direction B); length 2 km; DTV: 25 000 vehicles/d, driving direction A with feeder/exit road:
- Collision frequency in Direction A: $9.81 * 10^{-7}$ [1/vehicle*km] * 2 km * (25'000/3) * 365 = 6 accidents per year.
- Collision frequency in Direction B: $6.81 * 10^{-7}$ [1/vehicle*km] * 2 km * (25'000/2*3) * 365 = 8 accidents per year.

In total, 14 accidents are to be expected.

- Special characteristics with regard to bends and incline situations
- Permitted or effectively driven speed or options to influence traffic
- Existence of break-down bays and/or break-down lanes
- Frequency of tail-backs

The number of comparable tunnels is rather small, as there are a large number of additional, interacting factors. The accident analysis could therefore not determine quantitative correlations between the statistical collision rates and those factors. It can therefore be expected that the accident rate in a specific tunnel segment will deviate from the statistical means. The collision frequencies provided by the formula must therefore be corrected by a factor that has to be estimated for each investigation.

Detailed information concerning accident analysis and derivation of collision frequencies is provided in the Appendices 6 and 7.

Branching point 2: Accident types 1 / 3 / 6 / 7

The damage to persons and goods depends on the type and the course of the accident. This aspect was also investigated in the accident analysis (Appendix 6). The classification into categories according to [30] was used. The following factors influence the distribution:

- Tunnel type / traffic type
- Tunnel length
- Tunnel with or without feeder/exit roads

The following distribution of the conditional probability of a specific accident type was derived by the accident evaluation as a function of the factors mentioned above:

	Accident Type 1		Accident Type 3		Accident Type 6		Accident Type 7	
	With feeder/ exit rd.	Without feeder/ exit rd.	With feeder/ exit rd.	Without feeder/ exit rd.	With feeder/ exit rd.	Without feeder/ exit rd.	With feeder/ exit rd.	Without feeder/ exit rd.
One-way-traffic tunnel								
< 600 m	19.2%	46.2%	15.9%	0.0%	52.2%	23.1%	12.8%	30.8%
600 – 1200 m	10.2%	24.4%	9.1%	0.0%	72.6%	56.1%	8.2%	19.5%
≥ 1200 m	7.8%	12.8%	3.9%	0.0%	83.0%	78.5%	5.3%	8.7%
Two-way-traffic tunnel								
< 600 m	13.0%	15.2%	28.9%	0.0%	28.5%	50.0%	29.7%	34.8%
600 – 1200 m	7.1%	9.9%	13.3%	0.0%	63.5%	67.6%	16.2%	22.5%
≥ 1200 m	1.7%	2.7%	4.6%	0.0%	91.5%	93.6%	2.3%	3.7%

Table 3: Distribution of accident types

As the collision frequency, the distribution of accident types can also be affected by additional factors. However, no relevant correlations could be established by the accident analysis based on the available data.

Branching point 3: Distribution of the extent of damage

The extent of damage depends on the course and the specific circumstances of a collision. Risk analysis can only map such incidental boundary conditions to a limited extent. In order to be able to consider the possible spectrum of consequences of a collision, the accident analysis evaluated the distributions of the extent of damage for the four relevant accident types 1, 3, 6 and 7 and allocated them to classes according to distribution points [4]. The damage to goods was determined and the injured persons were allocated to “Damage to goods” according to the principles in ESAS [47].

While the estimates of the distribution of “Damage to goods” are derived on a sufficient statistical base, there are not enough data pertaining to accidents with fatalities. During the investigation period (a period of 3 years) a total of 6 accidents with fatalities happened. In each of the evaluated events, one person died. The values for the distribution of the extent of damage for “Fatalities” in Table 4 are therefore mainly based on assumptions.[12]

The following classes and the associated probabilities can be applied for determining the distribution of the extent of damage for the two damage indicators when using the method: [13]

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[12] This particularly applies to events with a large extent of damage (more than 30 fatalities). No empirical values are available for such very rare events, but then cannot be categorically excluded (e.g. collision of two tour buses, etc.)

[13] The damage to goods also includes the accident costs according to ESAS [47] for injured persons (€ 85 000.- per severely injured person and € 3 750.- per person with minor injuries). This was also considered in the accident analysis.

	No fatalities	1 fatalities	2-3 fatalities	4-9 fatalities	10-30 fatalities	>30 fatalities
Acc. Type 1	99.25%	0.59%	0.15%	0.01%	0.0001%	0.00001%
Acc. Type 3	99.50%	0.42%	0.07%	0.01%	0.0001%	0.00001%
Acc. Type 6	99.00%	0.72%	0.27%	0.01%	0.0001%	0.00001%
Acc. Type 7	99.50%	0.42%	0.07%	0.01%	0.0001%	0.00001%

Table 4: Distribution of the extent of damage for "Fatalities"

	up to € 8'000	€ 8'001 - 30'000	€ 30'001 - 150'000	€ 150'001 - 500'000	€ 500'001 - 1 Mio.	> € 1 Mio.
One-way-traffic tunnel						
Acc. Type 1	52.0%	34.0%	13.0%	0.89%	0.1%	0.01%
Acc. Type 3	81.5%	17.0%	1.0%	0.39%	0.1%	0.01%
Acc. Type 6	68.5%	19.5%	10.5%	1.39%	0.1%	0.01%
Acc. Type 7	83.0%	11.0%	3.0%	2.89%	0.1%	0.01%
Two-way-traffic tunnel						
Acc. Type 1	21.5%	60.5%	16.0%	1.89%	0.1%	0.01%
Acc. Type 3	76.0%	19.0%	3.0%	1.89%	0.1%	0.01%
Acc. Type 6	69.0%	29.0%	1.0%	0.89%	0.1%	0.01%
Acc. Type 7	60.0%	28.0%	11.0%	0.89%	0.1%	0.01%

Table 5: Distribution of the extent of damage for "Damage to goods" (incl. accident costs for injured persons)

An appropriate adaptation must be investigated, if it can be assumed with good reason that specific tunnel characteristics, for example an above-average proportion of heavy traffic, or special characteristics, for example the density of curves and the incline conditions, etc. will lead to a distribution of the extent of damage for the four accident types that differs significantly from the values in Table 4 and Table 5.

Branching point 4: Extent-of-damage class

This concerns allocating the extent of damage for the damage indicators "Fatalities" and "Damage to goods" to classes and determining the respective frequencies for the classes.

Branching point 5: Frequency per year

The scenario frequency results from multiplying the frequency of the initial event with all conditional probability along a certain route in the event tree.

Branching point 6: Expected extent of damage

The values in the right column are used as a replacement for the classes defined in the left column for the two damage indicators:

Extent-of-damage class	Expected extent
No fatalities	0 fatalities
1 fatalities	1 fatalities
2-3 fatalities	2 fatalities
4-9 fatalities	5 fatalities
10-30 fatalities	15 fatalities
>30 fatalities	35 fatalities

Table 6: Extent-of-damage classes for "Fatalities"

Extent-of-damage class	Expected extent
up to € 8'000	€ 1'000
€ 8'001 - 30'000	€ 5'000
€ 30'001 - 150'000	€ 30'000
€ 150'001 - 500'000	€ 300'000
€ 500'001 - 1 Mio.	€ 700'000
> € 1 Mio.	€ 1'200'000

Table 7: Extent-of-damage classes for "Damage to goods"[14]

Branching point 7: Aversion factor φ

The total damage caused by accidents in a road tunnel can be expressed in the collective risk, as described above. This value corresponds to the statistically expected extent of damage over several years (e.g. the statistically expected number of fatalities per year). Experience (in particular in connection with potentially large events) shows that collective risks are not only evaluated according to this expected damage, but that the possible extent of damage is an additional, important factor. Scenarios with identical collective risks and therefore equal statistically expected extents of damage are differently evaluated when there is a large difference in their extents of damage. Usually, accidents with a large impact on society are seen as much worse as a large number of small accidents with the same overall value of damage. Often, large accidents also cause larger, indirect damage. Usually, the risk analyses only deal with direct damage but do not explicitly consider consequential damage.

[14] see Footnote 13

The special weighting of large events as well as indirect damage that was not included can be considered by *risk aversion*. Risk aversion means that the “effective” extent of damage of an accident is weighted, where the weight increases with the extent of damage. An extent of damage of, for example, 10 fatalities is then treated as if it had a value of φ* 10 fatalities. φ is an aversion factor that depends on the extent of the damage. Additional information concerning risk aversion and the appropriate method is provided in Appendix 8.

When using this method for “Fatalities”, the following aversion factor φ is used as a function of the effective extent of damage:

$$\varphi = \sqrt{Extent\_of\_damage(fatalities)}$$

The aversion factor φ for “Damage to goods” is determined as follows:

Extent of damage to goods	Risk aversion factor φ
< € 5 million per event	1
≥ € 5 million per event	3

Table 8: Risk aversion factors for “Damage to goods” as a result of collisions

Branching point 8: Evaluated risk R_e

For collective risks that are weighted with an aversion factor, the term weighted (or “perceived”) collective risk R_e is used. It is determined as follows:

$$R_e = \sum_{i,k} H_{ik} \cdot A_{ik} \cdot \varphi_k\,(A_{ik})$$

R_e: Evaluated risk [fatalities/year] or [€/year]

H_{ik}: Accident frequency [1/year]

A_{ik}: Extent [fatalities, €, etc.]

φ(A): Aversion factor [-]

i: Identifies the event

k: Identifies the damage indicator (fatalities, damage to goods, etc.)

Branching point 9: Marginal costs

Experience shows that efforts to reduce risks that emanate from a system or an installation are only implemented up to a certain extent. The effort made for safety measures and the risks assessed as acceptable are obviously directly related. Adequate measures with regard to the cost-effectiveness are those where the ratio between (financial or monetarised) effort and increase in safety is still below a specified value that is considered as reasonable. This threshold value for cost-effectiveness is called “marginal costs”. It indicates a measure for the willingness to pay for risk-reducing measures. The marginal costs can be used to express the risks determined in monetary units.

Additional explanations concerning the principle of marginal costs and the approach of using cost-effectiveness as evaluation instrument are provided in Appendix 8 and Chapter 4.5. The following marginal costs should be assumed for the risks in road tunnels as a result of collisions:

- € 5 million per saved human life
- € 3.- per € 1.- prevented damage to goods

Branching point 10: Monetarised risk R_m

The evaluated risk R_e is monetarised by multiplying it with the marginal costs.
The monetarised risk R_m is therefore calculated as follows (and as already described above):

$$R_m = \sum_{i,k} H_{ik} \cdot A_{ik} \cdot \varphi_k (A_{ik}) \cdot G_k$$

R_m:	Monetarised risk [€/year]
H_{ik}:	Accident frequency [1/year]
A_{ik}:	Extent [fatalities, €, etc.]
$\varphi(A)$:	Aversion factor [-]
G_k:	Marginal costs [€/damage unit]
i:	Identifies the event
k:	Identifies the damage indicator (fatalities, damage to goods, etc.)

4.3 Scenario type "Fire without hazardous goods according to the ADR"

4.3.1 Scenario definition

The scenario type “Fire without hazardous goods according to the ADR” includes the following sub-scenarios:

- Fire with a thermal power of 5 MW (e.g. burning passenger car)
- Fire with a thermal power of 30 MW (e.g. burning truck/tour bus)
- Fire with a thermal power of 50 MW (e.g. burning truck)
- Fire with a thermal power of 100 MW (e.g. two trucks burning after collision)

Additional, illustrated explanations for possible event sequences and scenarios are provided in Appendix 4.

The scenario “Fire without hazardous goods according to the ADR” also includes fires as a result of breakdowns or collisions. Fires as a result of operating equipment faults are of low importance and have therefore not been considered. Also not considered were fires in collection with hazardous goods, as separate procedures are available for this purpose that make use of the OECD/PIARC model [16] or of equivalent models.

4.3.2 Event tree

Figure 9 and Figure 10 show the structure of event trees for the scenario “Fire”. The section shows the branching points in the event tree and contains the elements “Calculation of the extent” (incl. monetary risks), individually numbered from 1 to 14. The complete event trees for the two damage indicators considered are shown in Appendix 5.

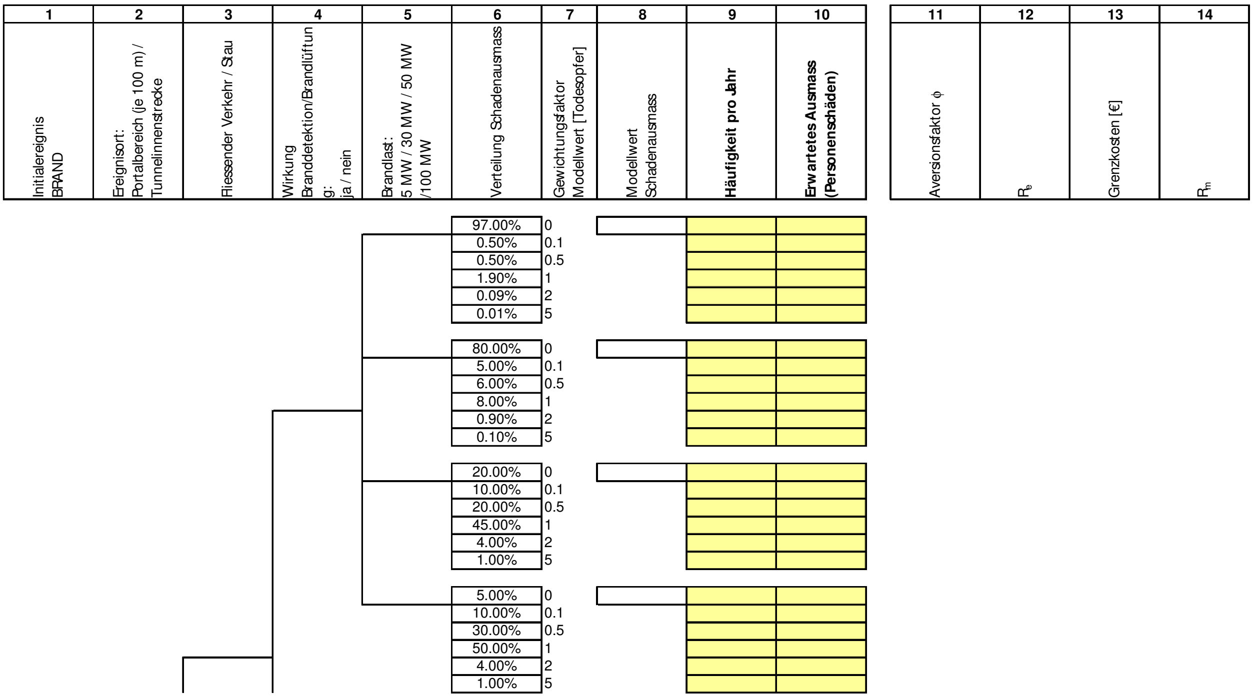

Figure 9: Structure of the event tree for scenario type “Fire without hazardous goods according to the ADR” for the damage indicator “Fatalities”

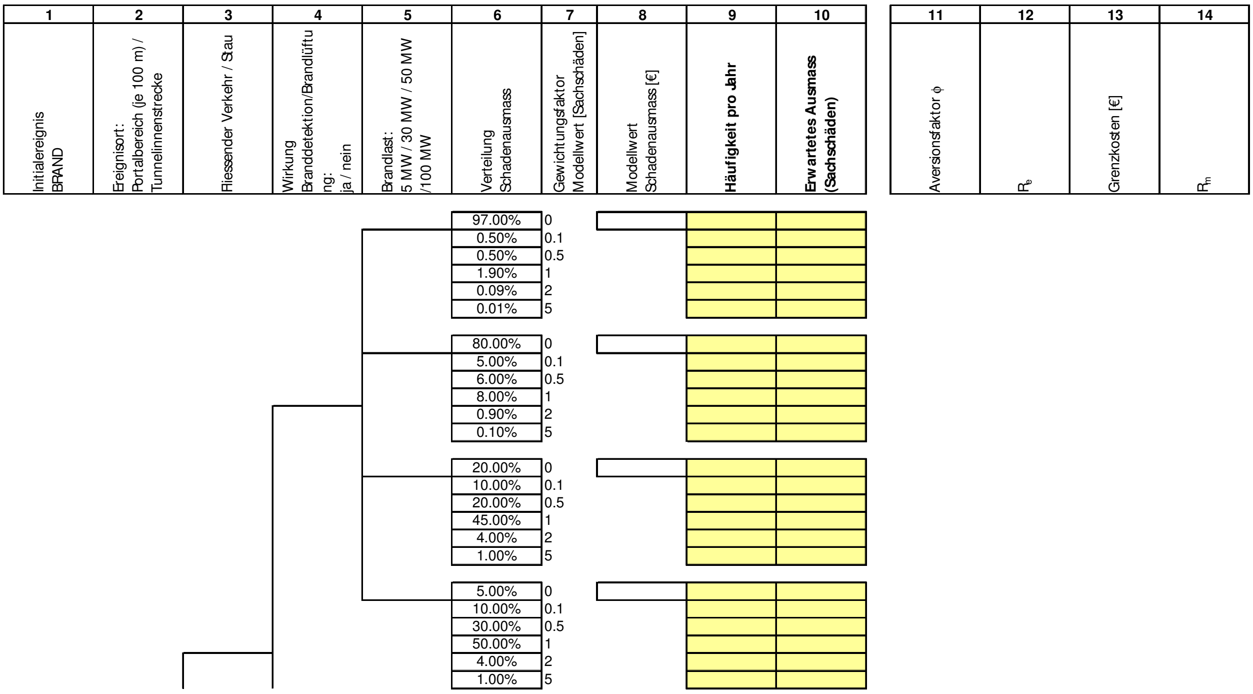

Figure 10: Structure of the event tree for the scenario type "Fire without hazardous goods according to the ADR" for the damage indicator "Damage to goods and injured persons"

The factors for determining the frequencies/probabilities and the resulting extents of damage as well as the required procedural steps for the calculation of risks as a result of a fire are described below. The procedural steps are structured according to the branching points in the event tree.

4.3.3 Event frequencies, extents of damage and resulting fire risks

Branching point 1: Initial event fire

Fires in road tunnels are generally rare events and are mainly the consequence of a breakdown, a technical fault (e.g. engine fire) or a collision. Experience shows that the main causes of fire are technical faults.

The accident evaluations have shown that in total only 3 fires happened as a result of collision during the study period of 3 years.[15] Consequently, there is little statistical information concerning the initial event "Fire".

The initial frequency of a fire is therefore estimated by estimating the probabilities of the two causes separately:

[15] The events are fires resulting from collisions. No accident protocols concerning fires as a result of technical faults were available for evaluation.

- *Frequency of a fire as a result of a collision:* Three fire events as the consequence of a collision were found in the accident analysis. This corresponds to a fire rate of 25% as a result of e previous collision. Values from literature are comparable. A NSTHA report [46] mentions a fire rate of 0.3% as a result of accidents. Collision rates can therefore be adjusted with a factor 0.003 to estimate the frequency of fires as a result of collisions. Assuming a mean collision rate of $6 * 10^{-7}$ [1/ (vehicle*km)] results in a fire frequency as a result of collisions of $2 * 10^{-9}$ [1/ (vehicle*km)].
- *Frequency of a fire as a result of a technical fault:* An analysis of a statistic of fires in the Elbtunnel resulted in a fire frequency (all causes) of approx. 10^{-7} [1/(vehicle*km)].[16] However, it must be considered that most of these fires only led to small damage to goods and are therefore of minor importance for the question at hand. According to the information in the PIARC report "Road Safety in Tunnels" [44], the proportion of fires that lead “neither to injuries nor damage to goods” is in the rage of 80% to 90%. Given the fact that the present method only considers fires with a thermal power of at least 5 MW (corresponds to a completely burned-out passenger car), it can be assumed that 95% of all fires do not lead to relevant damage. This leads to a frequency of relevant fires of $4.5 * 10^{-9}$ [1/(vehicle*km)]. When one subtracts the fire frequency as a result of collisions, a fire frequency of approx. $3 * 10^{-9}$ [1/(vehicle*km)] results for vehicle fires as a result of technical faults.

The following procedure is therefore appropriate for estimating the frequency of a fire:

1. Estimate the collision frequency (see Chapter 4.2.3) and adjust the resulting value with the percentage of fires after collisions (0.3%).
2. Add the frequency of fires as a result of technical failures based on a frequency of fires of $3 * 10^{-9}$ [1/(vehicle*km)]. It has to be assumed that the frequency of technical defects is proportional of the length of the tunnel and the traffic load.

If a different fire frequency is to be expected due to specific characteristics of the tunnel segments, the value provided must be adjusted by an (estimated) investigation-specific factor.

Branching point 2: Event location: Portal area / road inside the tunnel

Unlike collisions, fire scenarios consider the location of the fire, as the portal areas (inlet and outlet area) differ with regard to the exposure of the person and the escape options and therefore with regard to the potential extent of damage.

[16] This value is also shown in the PIARC study "Fire and Smoke Control in Road Tunnels" [43].

An estimate of the conditional probability of a fire in one of the two areas, the length of these areas must be compared with the total length of the tunnel or the tunnel segment. A length of 100 m has to be assumed for each of the portal areas.[17]

For a tunnel segment with a total length of 1 km, the conditional probability that a fire occurs in the portal area is 20% ((2*100 m)/1000 m). The conditional probability that the fire occurs at the inside of the tunnel is therefore 80%.

Branching point 3: Flowing traffic / tailback

Whether a fire occurs when traffic is normal, during a tailback or when traffic is heavy affects the number of exposed persons and therefore the potential extend of the damage.[18] The conditional probability can be estimated from the number of the annual tailback hours (proportion of the tailback-hours per year at 8760 hours). If the number of the tailback hours for a tunnel or tunnel segment is at 300 hours per year, a value of 3.5% (tailback hours / hours in a year) or 96.5% must be entered in Column 3.

Branching point 4: Effect of fire detection / fire ventilation

When a fire occurs, it is of prime importance that the fire is detected as fast as possible and that the tunnel ventilation starts the fire program. For these systems (as for many other tunnel infrastructure systems) there are practically no basic or survey data concerning possible operating faults or derived failure probabilities available.[19] In addition to missing basic data, the systems currently installed in tunnels further show considerable variation with regard to the design and layout of detection and ventilation systems. The probability of detecting a fire therefore depends strongly on the respective detection system (visibility measuring system, line-type fire detectors, etc.) or the combined effects of several detection systems installed in a tunnel.

It is therefore recommended to estimate the appropriate failure probability by using simple fault trees.[20] The following Figure 11 shows an example of such a fault tree.

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[17]The accident analysis and other, comparable statistical evaluations usually show a higher accident rate in the portal area as compared with the road inside the tunnel. Given the fact that the majority of fires results from technical faults (which can be assumed as location-independent) this aspect was not further investigated for the method.

[18] Also the potential for damage to goods as a result of a fire is higher in tail-back situations.

[19] An evaluation within this research project has shown that in most cases information is only available from the manufacturer of the tunnel infrastructure system, which usually is only based on estimates. No systematic documentation and evaluation of operating faults in existing tunnels was found during the investigations. There are only evaluations of single events that do not permit statistical evaluation.

[20] It must be noted that also here several assumptions will have to be made, as not all basic data are will be available.

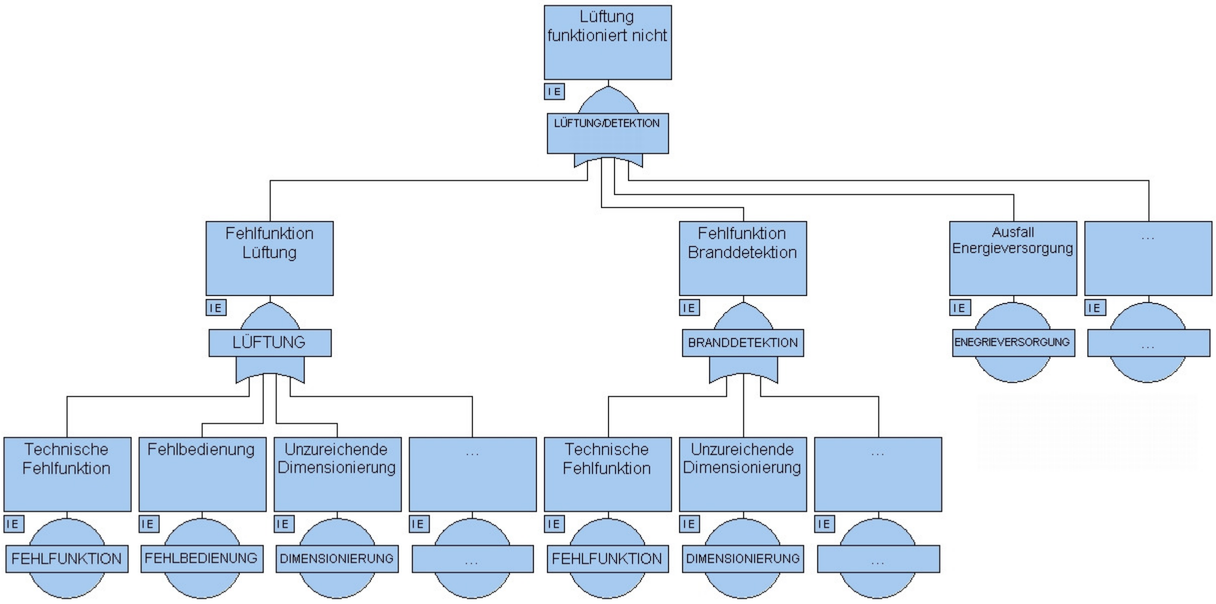

Figure 11: Section of a sample fault tree for estimating the failure probability for the ventilation/fire detection system

For an initial, rough estimate, it can be assumed that the systems will fail or work insufficiently in 1% of all fire incidents.

Branching point 5: Thermal power: 5 MW / 30 MW / 50 MW / 100 MW

The thermal power has a significant impact on the resulting extent of damage. While the fatalities are mainly determined by the effect of the smoke gas created, the damage to goods is determined by the effect of the heat.

The resulting thermal power depends mainly on the material burnt (type of vehicle, load, etc.) and may vary depending on the circumstances. Four cases are used to map the spectrum of thermal power.

The accident analysis does not permit statistical evaluation of the distribution of the different thermal powers. Also the literature provides little information. However, it can be assumed that fires with high thermal powers (50 MW or 100 MW) mainly occur as a result of collision and only rarely as a result of technical faults. It can further be assume that small fires clearly dominate the thermal power spectrum. It is therefore assumed that at most every tenth fire exceeds a thermal power of 5 MW.

The following, simplified distribution is assumed:

- Thermal power of 5 [MW]: 90.00%
- Thermal power of 30 [MW]: 9.90%
- Thermal power of 50 [MW]: 0.09%
- Thermal power of 100 [MW]: 0.01%

If a tunnel has a proportion of heavy traffic that significantly deviates from the average, an adaptation of the assumption must be considered.

Branching point 6: Distribution of the extent of damage

In contrast to collisions, the statistical results do not support reliable conclusions concerning the distribution of the extent of damage.[21] However, there are simulation models available for determining the extent of damage (also see Column [8], model values for extent of damage). In order to map the uncertainties in the models and situation-specific coincidences, a specific distribution of the extent of damage determined by the models is assumed. Small fires are more likely to cause no or only minor damage to persons or goods than large fires, which facilitates assumptions concerning the distribution of the extent of damage as a function of thermal power. Information concerning this distribution for determining the extent of damage as well as additional, relevant factors is listed in Table 9.

The distribution of the respective extents of damage can be affected by organisational and/or technical or constructive measures. Examples are:

[21] For collisions, statistical basic data can be used. For fires greater than 5 MW there are hardly any data, due to the low number of such events.

- Organisational measures:
  - Emergency services and rescue units (stationed locally,[22] technical means and staff, training level, etc.)
  - Information of the traffic participants in an emergency: If effective measures in the event of a fire inform the traffic participants quickly and successfully about the need to escape, the extent of damage is reduced accordingly.
- Technical/constructive measures: SOS niches with fire extinguishers, fire fighting devices, etc.

Branching point 7: Weighting factor for model values

In order to map the distribution of the extents of damage mentioned under *Branching point 6* and the basic values determined by models (fire fume spreading models, escape simulation models, etc.), the model values are appropriately weighted or adjusted. The adjustment factors for the model values as well as the respective, relative proportion are provided in Table 9 and Table 10 below (the values are based on assumptions).

Scaling factor	Thermal power 5 MW	Thermal power 30 MW	Thermal power 50 MW	Thermal power 100 MW
0 * model value	97.00%	80.00%	20.00%	5.00%
0.1 * model value	0.50%	5.00%	10.00%	10.00%
0 5 * model value	0.50%	6.00%	20.00%	30.00%
1* model value	1.90%	8.00%	45.00%	50.00%
2 * model value	0.09%	0.90%	4.00%	4.00%
5 * model value	0.01%	0.10%	1.00%	1.00%

Table 9: Assumptions concerning the distribution of the extent of damage as a function of the values determined in models (situation: ventilation works)

[22] For the risk analysis, the time between the start of the fire and the intervention is of primary importance. Local placement is only one relevant aspect. Other factors such as alarm time, opportunities for access, etc. are also important).

Scaling factor	Thermal power 5 MW	Thermal power 30 MW	Thermal power 50 MW	Thermal power 100 MW
0 * model value	95.00%	65.00%	20.00%	5.00%
0.1 * model value	0.50%	8.00%	10.00%	10.00%
0 5 * model value	0.50%	10.00%	20.00%	30.00%
1* model value	4.00%	15.00%	45.00%	50.00%
2 * model value	0.09%	1.90%	4.00%	4.00%
5 * model value	0.01%	0.10%	1.00%	1.00%

Table 10: Assumptions concerning the distribution of the extent of damage as a function of the values determined in models (situation: no ventilation)

Branching point 8: Model value "Extent of damage"

Damage indicator "Fatalities"

Escaping tunnel users can be hindered by the effect of smoke and heat. Smoke causes damage through the soot particles released by the fire and the smoke gas generated by combustion. Even low concentrations of soot particles lead to significant reduction of vision and orientation and cause strong irritation of the respiratory pathways and the mucosa. The toxic effect of combustion products such as carbon monoxide and hydrocyanic acid depends on their concentration and the duration of exposure. The effect of heat on the human organism also depends, in addition to the temperature, on the duration of exposure. All three components: soot particles, smoke gas concentration and temperature can separately or in combination cause the tunnel user to abandon the escape. However, analysis of fire event shows that smoke is the primary cause of abandoning an escape.

Relationship between visibility range and escape speed

Empirical investigations concerning escape behaviour under the influence of smoke show that the escape speed is directly proportional to the local visibility range [45]. Figure 12 shows that a drastic reduction of the escapes speed can be expected below a visibility range of 10 m. This reduction depends on the composition of the smoke. Real vehicle fires usually cause strong irritation of the eyes, which makes movement below a visibility range of 5 m impossible. It has to be taken into account that loss of orientation happens earlier. Purposeful movement to emergency exits is only possible when they are recognised or when appropriate installations guide the escaping persons in the right direction. For a person escaping in a tunnel, this implies that he must at least be able to see the escape route signs. If they have a distance of 25 m, escaping persons must be able to see them at this distance in an extreme situation.

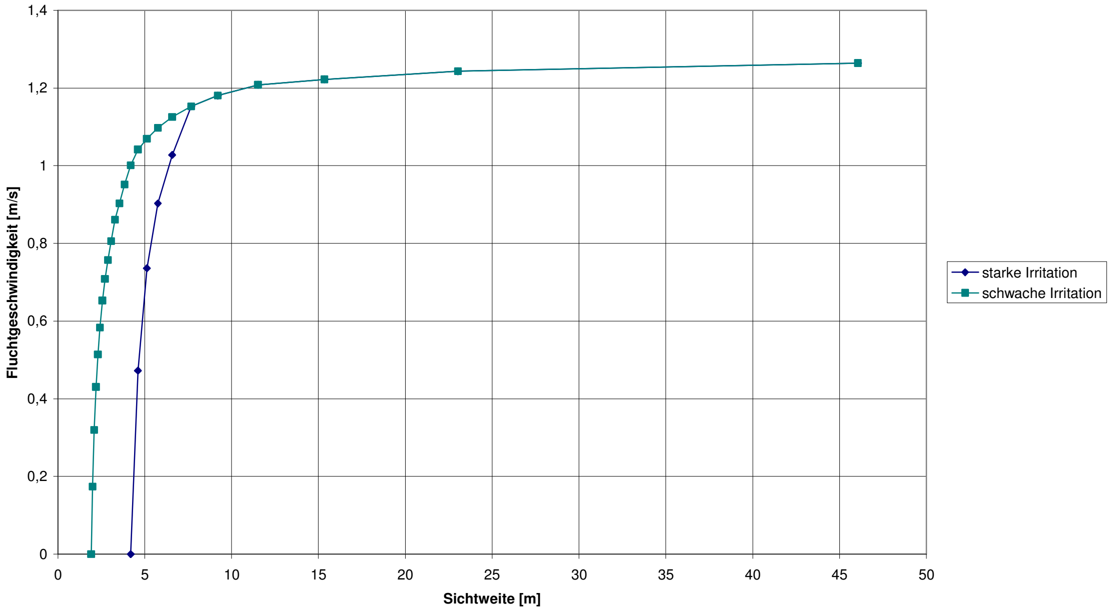

Figure 12: Correlation between visibility range for reflective objects and escape speed according to Mayer, [45]

Toxicity of smoke gas

Real fires usually emit a range of toxic pollutants from the origin of fire to the environment. Of the multitude of components contained in smoke from fires, mainly carbon monoxide (CO) and hydrocyanic acid (HCN) are acutely toxic for humans. Both gases have a narcotic effect, even in low concentrations. Extended exposure or higher concentrations rapidly lead to death.

Carbon monoxide is produced in practically all combustion processes as a result of incomplete combustion. It belongs to the group of colour and odourless gases. It also has a low solubility in water and penetrates therefore into the deep regions of the lung. Its affinity to haemoglobin in the blood is approx. 250 times stronger than that of oxygen, which is the reason for its toxicity. The carboxyhaemoglobin (CO-Hb) created reduces the oxygen transport by the blood. The first toxic effects appear at a proportion of approx. 20% CO-Hb in the blood. At approx. 40% lead to loss of consciousness. CO-Hb concentrations of 50% to 70% lead to death.

Hydrocyanic acid is approx. ten times more toxic than carbon monoxide (see Figure 13). It is produced during the combustion of materials containing nitrogen, which include acrylic, nylon, polyurethane and wool. In contrast to carbon monoxide, hydrocyanic acid gas is highly soluble in water and can therefore enter the human organism orally as well as by inhalation. Studies show that already short-term exposure to concentrations of 180 to 270 ppm in the respiratory air lead to death and that a concentration of 90 ppm is lethal after prolonged exposure.

Both smoke gases can unfold their toxic effects independently of each other, i.e. their effects can be additive.

Figure 13 shows the concentrations of carbon monoxide (CO) and hydrocyanic acid (HCN) as a function of the exposure time after which loss of consciousness can be expected.

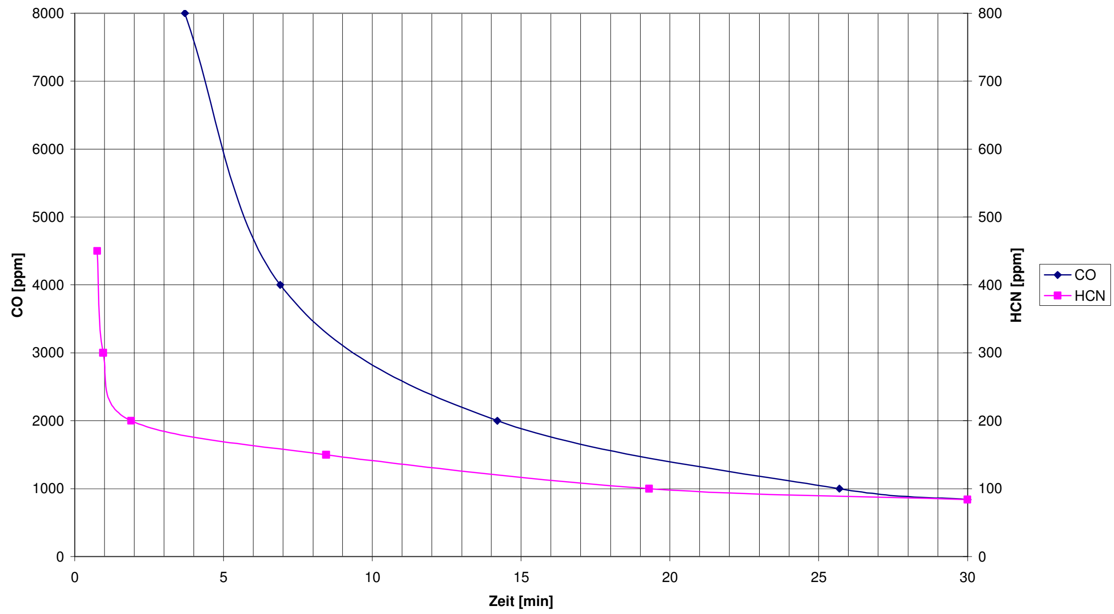

Figure 13: Loss of consciousness as a function of time and concentration according to Mayer, [45]

Effects of temperature on the human organism

The energy released by a fire can have damaging effects on humans due to heat radiation or convective heat transfer. Effects due to heat radiation are usually restricted to the immediate vicinity of the fire, which convective heat transfer can transport heat over large distances. Depending on the exposure time, the associated increase of environmental temperature can lead to a heat build-up in the human body or to burns. Short exposures do not lead to a heat build-up in the human body, as the body has a certain heat capacity. However, even short exposures can lead to burns of the skin and the respiratory tract.

In addition to the environmental temperature, the type of injuries is also strongly influenced by the humidity content of the air. Figure 14 shows the experimentally determined threshold temperature curves by Crane (1978) and Purser (1995) as a function of the exposure time. According to Purser (1995), dry air with temperatures up to 120 °C will mainly cause heat build-up. Temperatures above 120 °C cause burns of the skin.

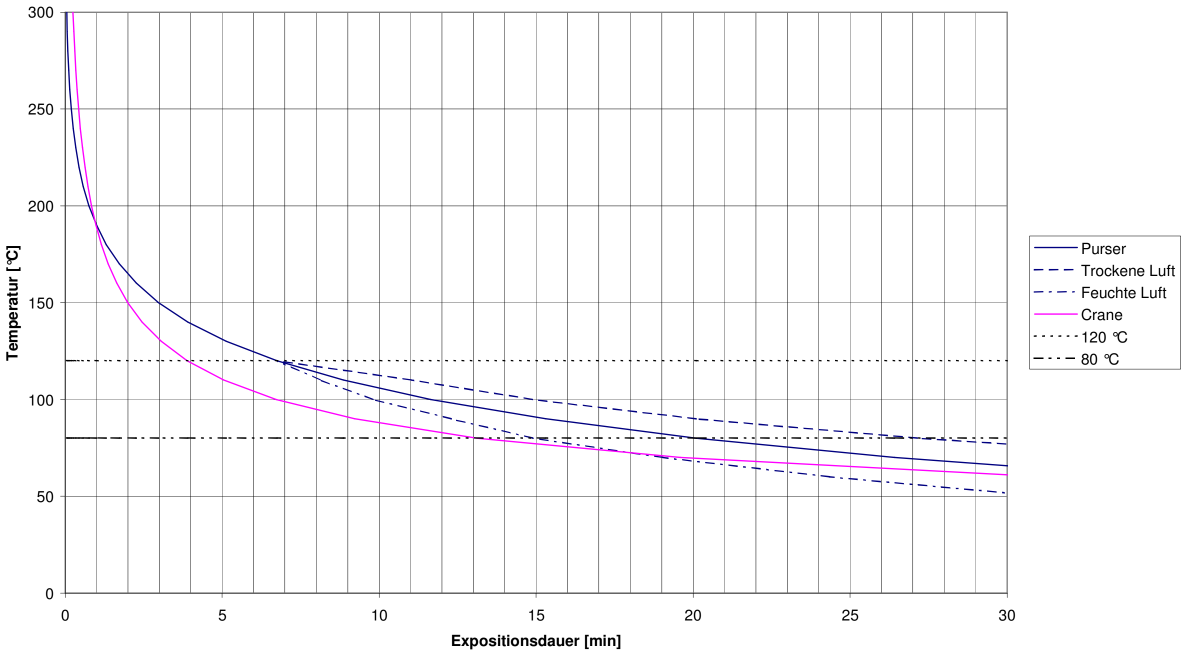

Figure 14: **Detrimental effects on the human organism as a function of exposure time and environmental temperature**
according to Mayer, [45]

Model requirements

Estimates of injuries require information about concentration and temperature distributions in space and time. These values can be calculated by solving the time-dependent equations for mass, impulse, energy and material conservation for the three spatial dimensions. This requires the use of numerical methods, as these equations are too complex to be solved by analytical means. Suitable CFD (Computational Fluid Dynamics) models exist, for example the Fire Dynamic Simulator (FDS). Their basic suitability for calculating the required values has already been proven in the research project “Fire tests in road tunnels - simplification of the execution” (FE 03.375/2004/FGB). CFD models can simulate tunnels on a very fine scale when the relevant factors such as geometry, ventilation, traffic, weather, etc. are taken into account. However, the application of CFD models requires considerable calculation effort and time. The simulation of whole tunnel systems is therefore usually performed on computer clusters or mainframe computers.

In addition to CFD models, simpler (one- or two-dimensional) models exist, which require a lower calculation effort but are less accurate with respect to the spatial resolution of the results. Experience has shown that it is necessary to investigate, which models are suited for a specific study. The use of CFD models for very long tunnels may be too resource-intensive for practical use, but simpler models might consider complex factors such as detailed tunnel geometry, complex ventilation systems or weather conditions only very roughly or not at all.

Determining the extent of damage with self-rescuing areas

In the event of a fire, tunnel users must move independently to safe areas to evade the effects of temperature and smoke. Successful escape to safe areas strongly depends on the local visibility conditions. The relationship between visibility range and escape speed is therefore used for assessing the escape conditions. The area from which self-rescue is still possible under specified conditions can be determined from the soot concentrations that determine the visibility range and thereby the escape speed and the given lengths of the escape routes. The definition of self-rescue areas must in principle discriminate between safe and unsafe areas.

Less critical areas are tunnel sections in which the visibility range remains during all stages of the fire equal or larger than the distance of the escape route marker, which is 25 m according to RABT 2006, so that the use of self-rescue facilities is at no time obstructed by smoke. It is further assumed that the effects of smoke are low in the less critical areas, so that self-rescuing is not necessarily essential for survival.

The unsafe areas of the tunnel are grouped into areas in which successful self-rescue is possible and those where self-rescue is only possible under certain conditions or not at all. For visibility ranges larger than 5 m, an escape speed of up to 1.3 m/s is assumed. If the visibility range falls below 5 m, it is assumed that no movement is possible and that the self-rescue will fail.

Areas from which self-rescue can be successful are determined by the distance to the next emergency exit or portal that a tunnel user can cover at the assumed escape speed when he proceeds with the escape immediately after the alarm was given. Areas from which tunnel users can escape when they start the escape independently before the alarm is given by the operational systems, are termed conditional self-rescue areas. Areas from which an emergency exit or portal can not be reached in time at the assumed escape speed do not facilitate self rescue [45]. An example of the self-rescue areas resulting from at a longitudinal flow speed of 6.0 m/s and a distance between emergency exits of 150 m is shown in Figure 15.

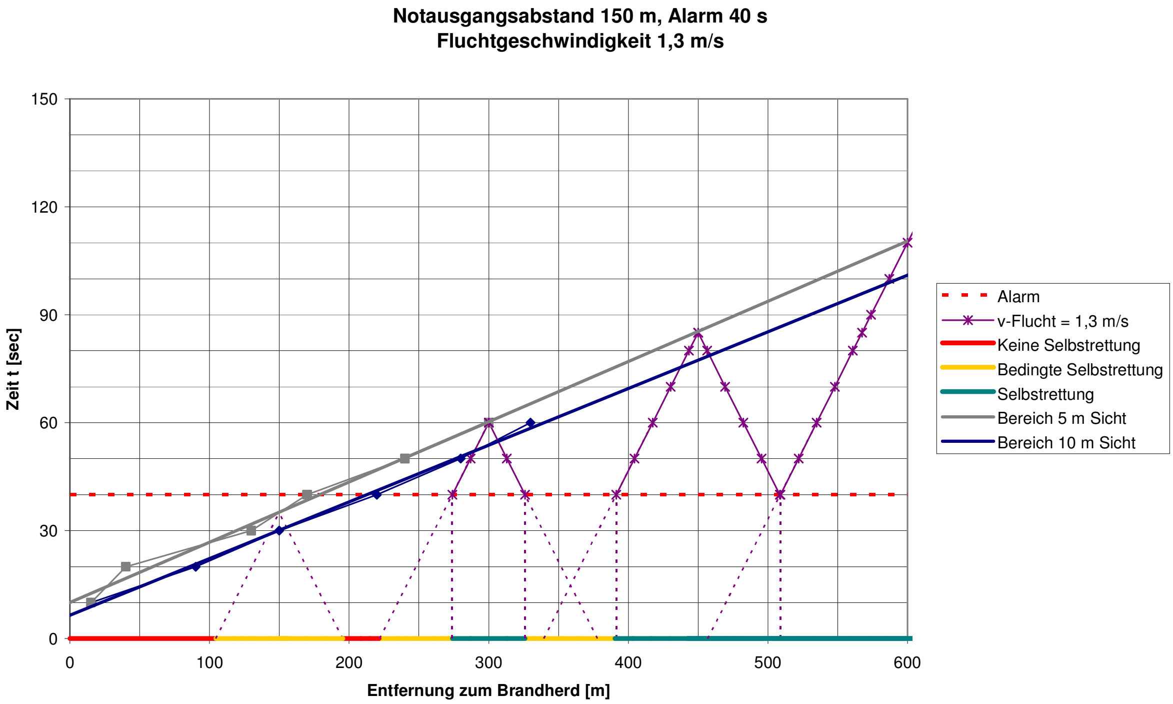

Figure 15: Self-rescuing areas at an emergency exit distance of 150 m, alarming of the tunnel users 40 s after the start of the fire
according to Mayer, [45]

<u>Damage indicator "Damage to goods and injured persons"</u>

The following pragmatic procedure is suggested for estimating damage to goods and damage to persons in the form of injured people:

- A course estimate of the number of injured persons can be derived from the damage indicator "Fatalities". It can be assumed that per fatality due to a fire, then additional persons are injured. It can further be assumed that 10% of the persons affected will have severe injuries and 90% minor injuries. The quantification of the injuries in monetary terms can be based on the same accident costs that were used for the scenario type "Collisions": € 87 000.- consequential accident damage for severely injured persons and € 3 750.- per person with minor injuries.

- The damage to goods can be estimated be using appropriate fire simulation models to derive a temperature distribution and considering the affected infrastructure on a project-specific basis. If basic data are lacking and a rough estimate is required, it can be assumed that the damage to goods is approx. 2 to 3 times larger than the costs for injured persons (according to the consequential costs budgeted).

Branching point 9: Frequency per year

The scenario frequency results from multiplying the frequency of the initial event with all conditional probabilities along the respective route in the event tree.

Branching point 10: Expected extent of damage

The expected extent of damage is determined by multiplying the model value for each sub-scenario (Branching point 8) with the appropriate weighting factor (Branching point 7).

Branching point 11: Aversion factor

As for the scenario type “Collision”, a risk aversion function is also considered for fires: Fatalities are weighted with the following aversion factor φ, which is a function of the effective extent of damage:

$$\varphi = \sqrt{Extent\_of\_damage(fatalities)}$$

The aversion factor φ for damage to goods is determined as follows:

Extent of damage to goods	Risk aversion factor φ
< € 5 million per event	1
≥ € 5 million per event	3

Table 11: Risk aversion factors for “Damage to goods” due to fire

Branching point 12: Weighted risk R_e

The weighted, collective risk R_e is determined in the same way as for the scenario type "Collision" (see Chapter 4.2.3).

Branching point 13: Marginal costs

The following marginal costs should be assumed for the scenario type “Fire”:

- €10 million per saved human life[23]
- € 3.- pro € 1.- prevented damage to goods

Additional explanations concerning marginal costs are provided in Appendix 8.

[23] The different marginal costs per saved human life for the scenario types “Collision” and “Fire” result from the different classification with regard to categories (collision: classified in Risk Category 2; fire: classified in Risk Category 3). Additional information concerning this issue is provided in Appendix 8.

Branching point 14: Monetarised risk R_m

The monetarised risk R_m for a sub-scenario in the event tree is determined by multiplying the weighted risk R_e with the marginal costs. This procedure is equivalent to the one for the scenario type “Collision”.

4.4 Risk calculation and presentation

The risks for the scenario types “Fire (without collision)” and “Fire without hazardous goods according to the ADR” for a tunnel or a tunnel segment can be determined with the procedure described. The risk is presented as follows:

- Risk indicators:
  - Collective risk “Fatalities”: The collective risk or the expected extent of damage per year with regard to “Fatalities” must be determined for the tunnel under investigation. If a tunnel consists of several tunnel segments, the respective values per tunnel segment have to be added.
  - Monetarised risk R_m: The monetarised risk R_m with regard to the damage indicators “Fatalities” and “Damage to goods and injured persons” must be determined for the tunnel under investigation. The value determined corresponds to the expected monetary damage per year. If a tunnel consists of several tunnel segments, the values per tunnel segment have to be added.
  - Information of traffic participants in the event of a fire: If effective measures inform the traffic participants quickly and successfully about the need to escape, the extent of damage is reduced accordingly.
- Cumulative curve in the damage frequency diagram: The cumulative curve for the damage indicator “Fatalities” for both scenario types must be shown for the tunnel under investigation (see Figure 5).

4.5 Risk evaluation and planning of measures

The risks determined are presented as risk indicator or in the form of a damage frequency diagram. This does not determine whether the risks are to be accepted or not. The question” Which risks are to be tolerated and are therefore classified as acceptable?" must be explicitly answered as part of the risk evaluation. In the same way as for the quantification of risks a clear statement concerning the remaining risks and the acceptability is required. The basis of the risk evaluation is the fact that a tunnel complying with RABT 2006 can be considered as safe.

While risk analysis has to be performed as objectively as possible, the nature of risk evaluation implies the use of values. It can therefore not remain the sole domain of experts and involves the directly affected decision makers, the legislative bodies in general and thereby the whole of society.

The fact that risk evaluation contains subjective elements does not imply that the requirements for transparency, standardisation and traceability of the evaluation method should be lower. Risks are determined in a quantitative manner, which suggests that they should be evaluated by quantitative criteria. A comprehensive and complex risk analysis has little purpose when the measures to be taken are then selected on a more or less intuitive basis. It is further necessary to discriminate between the evaluation method and the numeric representation of the evaluation criteria used. The method must comply with strict, logical requirement, while the numeric representation of the criteria remains subjective and can only be achieved by agreement of the parties involved.

The following basic method for risk evaluation is suggested, which is based on common practice in various countries: An acceptable maximum risk is defined, which may not be exceeded irrespective of the resulting costs for safety measures. The limit is determined according to experience for the risks to be expected, so that the most critical cases can be identified and appropriate, risk-reducing measures can be planned. Planning of additional safety measures in all other cases is based on principle of cost-effectiveness.

4.5.1 Evaluation of cumulative curves in the damage frequency diagram

It is suggested to use an absolute evaluation criterion in the form of acceptability ranges in the damage frequency diagram in order to comply with the requirements in the directives RABT 2006 and 2004/54/EGf for risk evaluation of tunnels with “special characteristics” and to ensure a standardised safety level.

The safety measures requested in the directive have the primary purpose of reducing risks to persons. The evaluation in the damage frequency diagram is therefore exclusively performed for the damage indicator "Fatalities".

The following procedure is suggested for evaluating risks by using the damage frequency diagram:

1. For the tunnel to be investigated, the frequencies and extents of damage with regard to the damage indicator "Fatalities” are determined for the respective sub-scenarios of the two event types “Collision (without fire)” and “Fire without hazardous goods according to the ADR” using event trees. The frequencies are standardised for a tunnel length of 1 km and one year to generate a standardised reference value. For the cost-effectiveness ratio, the risk aversion is not considered by including a risk aversion factor in the calculation, but implicitly, through the incline of the acceptability line.
2. For the tunnel to be investigated, the resulting cumulative curve (resulting from the respective scenarios for the tunnel segments belonging to the tunnel) is standardised for a

reference length of 1 km and entered in the damage frequency diagram as in the example shown in Figure 16.

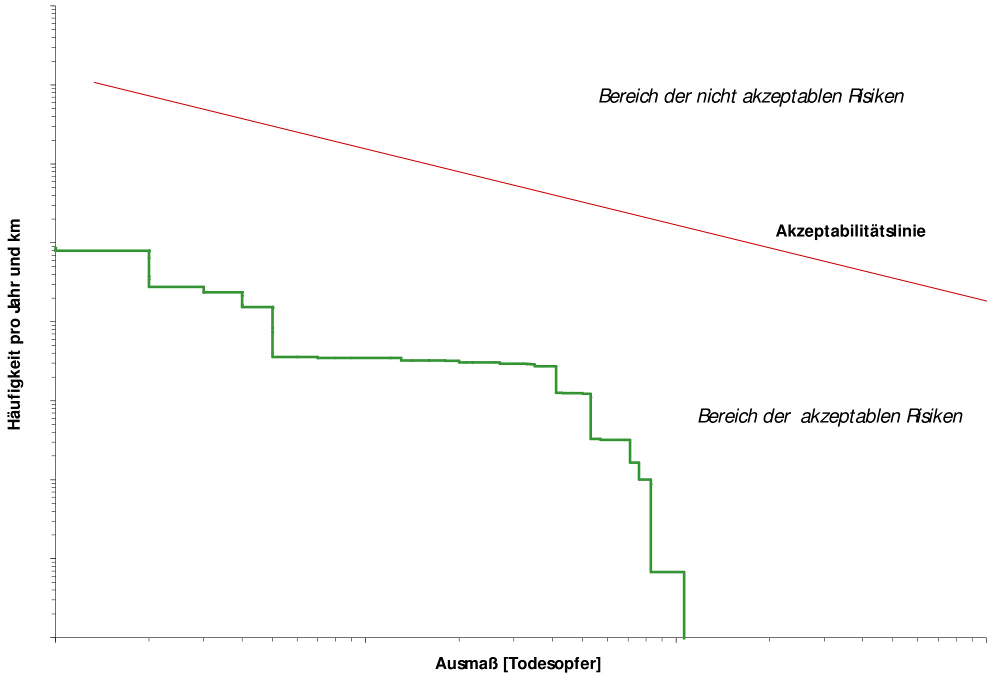

Figure 16: Damage frequency diagram with acceptability ranges (example)

3. If the standardised, cumulative curve is not in the range of the acceptable risks, additional safety measures have to be provided. The cumulative curve for the tunnel under investigation must then be re-determined, taking possible, additional/alternative measures into account, and re-evaluated with regard to its relative position to the acceptability line. If the newly determined cumulative curve is still not within the acceptable area of the damage frequency diagram, additional measures must be investigated or implemented.

The acceptability line in the damage frequency diagram implicitly also determines the limit for the maximum permitted collective risk. The selection of the location and the incline of the acceptance line further determines the permitted shape of the cumulative curve and thereby the characteristics of the risks evaluated as acceptable.

The acceptability line is determined with the purpose of defining a standardised, minimum safety level. This should be done while keeping feasibility in mind. While the evaluation based on marginal costs or cost-effectiveness can partially draw on objective parameters (direct and indirect consequential costs resulting from the death of a person), determining of the acceptability line in the damage frequency diagram is mainly based on a subjective consensus approach.

The findings currently derived in this research project do not support a practical suggestion for placing the acceptability line.[24] Such a suggestion has to be based on an investigation of the safety level of tunnels that comply with the regulations. The results can then be used to develop a suggestion for the type, position and gradient of an acceptability line. Until this has been achieved, risk evaluation has to be based on the comparison of the monetarised risks R_m [€/year] between the planned status (deviation from the directive or special characteristic) and the corresponding value of a theoretical structure that complies with the regulations.[25]

4.5.2 Evaluation of measures according to cost-effectiveness

The requirements of the directives RABT 2006 and. 2004/54/EG must be adhered to. If the regulatory requirements according to the directives cannot be implemented for a specific tunnel. appropriate, alternative safety measures have to be provided. The following procedure should be followed:

1. For the planned, alternative measures, the risk-reducing effect as well as the costs resulting from the implementation and operation must de determined. The annual costs K_{year} must be determined to evaluate the planned alternative measures according to cost-effectiveness. These comprise of:

   - Investment costs (K_{invest})
   - Operating and maintenance costs per year ($K_{operating}$)

   The resulting, annual costs can be calculated as follows:

$$K_{Jahr} = K_{Invest} \cdot \frac{(1+d)^n \cdot d}{(1+d)^n - 1} + K_{Betrieb}$$

where:

K_{year}:	Annual costs [€/year]
K_{invest}:	Investment costs [€/km]
$K_{operating}$:	Operating/maintenance costs [€/year]
n:	Life span [years]
d:	Discount rate / annuity factor [%] (typically in the range of 2%)

The costs of measures have to be converted to annual costs in the same way as risks or risk reductions.

[24] The incline of the acceptability line can be based on the aversion function selected.

[25] It becomes clear that individual EU states developing the method will handle the risk evaluation based on a comparison of the collective risks for the indicator "Fatalities". However, for the present method it is recommended to undertake the comparison based on monetarised collective risks. The reason is that this risk indicator also considers the aversion function. It is therefore better suited to map the shape of the cumulative curve then the collective risk. This value can further more by directly used for measures evaluation based on cost-effectiveness.

The costs of the measures have to be determined per projects. A rough cost estimate can be provided based on the estimated costs listed in Appendix 9.

The relationship between measures, their costs and their risk-reducing effects of measures can be shown in a diagram with the axes "Risk" and "Costs", as illustrated in Figure 17.

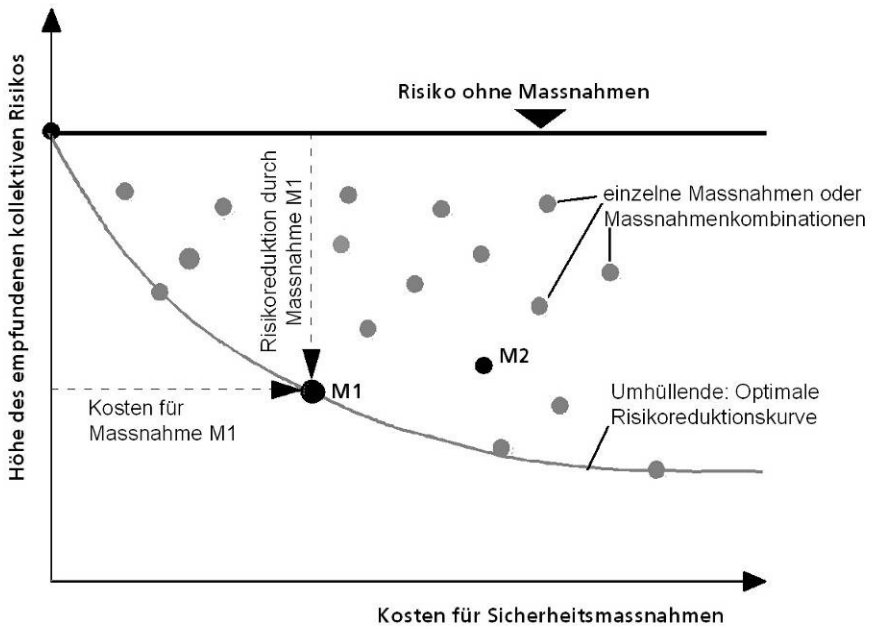

Figure 17: Risk reduction and costs for additional safety measures

Each safety measure, represented by its costs and its risk-reducing effect, can be displayed as point in the diagram in Figure 17.

2. The measures are evaluated by the cost-effectiveness ratio. The costs (K_{year} or ΔK) as well as the effect (R_m or ΔR) relate to one year and are expressed in monetary units [€]:

$$Cost - effectiveness - ratio = \frac{K_{year}}{R_m} = \frac{\Delta K}{\Delta R}$$

If the ratio is smaller than 1, the measure is cost-effective or appropriate, i.e. the effect is bigger than the costs.

The estimates for cost and risk reduction have a certain uncertainty. Therefore, the following criteria are stipulated for evaluations based on cost-effectiveness ratios:

- Cost-effectiveness ratio < 1: Measures must be implemented
- 1 ≤ cost-effectiveness ratio < 2: Implementation of measures to be checked on case-by-case basis

- Cost-effectiveness ratio ≥ 2: Measures not cost-effective

5 Case study

The current method was applied to five case studies. This chapter shows a sample application of the method for one case study. The results for the other case studies are summarised in Appendix 10.

5.1 Information concerning the tunnel

Table 12 shows the most important data that characterise the tunnel under investigation.

Tunnel parameter	Section 1	Section 2
Traffic type	One-way traffic, declining	One-way traffic, inclining
No. of lanes per direction	3	2
Lane width	3.75 m	3.75 m
Breakdown lane	-	-
Clear width	14.6 m	11.2 m
Clear height	8.2 m	6.7 m
Length	704 m	704 m
Min. longitudinal incline	3.0%	-3.0%
Max. longitudinal incline	3.0%	-3.0%
Permitted speed	100 km/h	100 km/h
Ventilation system	Longitudinal ventilation	
Emergency exits / escape routes	1 emergency exit in the middle of the tunnel	
DTV	38'800 vehicles/d	
Proportion of heavy traffic	16.4 %	
Tailback hours	250 hours/year	

Table 12: Characteristic of the case study tunnel investigated

5.2 Scenario type “Collision (without fire)”

Table 13 summarises the most important factors for determining the event frequencies and extents of damage for the scenario type “Collision”:

Branching points in the event tree	Comments
[1] Initial event “Collision”	Based on a traffic volume of 38 800 vehicles per day or 19 400 vehicles per day per tunnel segment, a statistical accident frequency of 1.13 accidents per year for one tunnel segment or 2.26 accidents per year for the whole tunnel can be estimated.
[2] Accident type	Tunnel without feeder/exit road, length class: 600 m – 1 200 m Acc. Type 1: 24.4% Acc. Type 3: 0.0% Acc. Type 6: 56.1% Acc. Type 7: 19.5%
[3] Distribution of the extent of damage	Evaluation of Table 4 (and Table 5 or Table 6 and Table 7)
[5] Frequency per year	The scenario frequency results from multiplying the frequency of the initial event with all conditional probabilities along the appropriate route in the event tree.

Table 13: Most important branching points for the event tree for collision, case study

An example of the event tree for the damage indicator “Fatalities” is shown in Figure 18.

1 Initialereignis KOLLISION	2 Unfalltyp: 1 / 3 / 6 / 7	3 Verteilung Schadenausmass	4 Schadenausmassklasse (Personenschäden)	5 **Häufigkeit pro Jahr**	6 **Erwartetes Ausmass (Personenschäden)**	7 Aversionsfaktor ϕ	8 R_e	9 Grenzkosten [€]	8 R_m
	24.4%	99.25000%	Keine Todesopfer	2.74E-01	0	0.0	0.0E+00	5.0E+06	0.0E+00
		0.59000%	1 Todesopfer	1.63E-03	1	1.0	1.6E-03	5.0E+06	8.1E+03
		0.15000%	2-3 Todesopfer	4.14E-04	2	1.4	1.2E-03	5.0E+06	5.8E+03
		0.01000%	4-9 Todesopfer	2.76E-05	5	2.2	3.1E-04	5.0E+06	1.5E+03
		0.00010%	10-30 Todesopfer	2.76E-07	15	3.9	1.6E-05	5.0E+06	8.0E+01
		0.00001%	> 30 Todesopfer	2.76E-08	35	5.9	5.7E-06	5.0E+06	2.9E+01
	0.0%	99.50000%	Keine Todesopfer	0.00E+00	0	0.0	0.0E+00	5.0E+06	0.0E+00
		0.42000%	1 Todesopfer	0.00E+00	1	1.0	0.0E+00	5.0E+06	0.0E+00
		0.07000%	2-3 Todesopfer	0.00E+00	2	1.4	0.0E+00	5.0E+06	0.0E+00
		0.01000%	4-9 Todesopfer	0.00E+00	5	2.2	0.0E+00	5.0E+06	0.0E+00
1.13E+00		0.00010%	10-30 Todesopfer	0.00E+00	15	3.9	0.0E+00	5.0E+06	0.0E+00
		0.00001%	> 30 Todesopfer	0.00E+00	35	5.9	0.0E+00	5.0E+06	0.0E+00
	56.1%	99.00000%	Keine Todesopfer	6.28E-01	0	0.0	0.0E+00	5.0E+06	0.0E+00
		0.72000%	1 Todesopfer	4.56E-03	1	1.0	4.6E-03	5.0E+06	2.3E+04
		0.27000%	2-3 Todesopfer	1.71E-03	2	1.4	4.8E-03	5.0E+06	2.4E+04
		0.01000%	4-9 Todesopfer	6.34E-05	5	2.2	7.1E-04	5.0E+06	3.5E+03
		0.00010%	10-30 Todesopfer	6.34E-07	15	3.9	3.7E-05	5.0E+06	1.8E+02
		0.00001%	> 30 Todesopfer	6.34E-08	35	5.9	1.3E-05	5.0E+06	6.6E+01
	19.5%	99.50000%	Keine Todesopfer	2.19E-01	0	0.0	0.0E+00	5.0E+06	0.0E+00
		0.42000%	1 Todesopfer	9.25E-04	1	1.0	9.3E-04	5.0E+06	4.6E+03
		0.07000%	2-3 Todesopfer	1.54E-04	2	1.4	4.4E-04	5.0E+06	2.2E+03
		0.01000%	4-9 Todesopfer	2.20E-05	5	2.2	2.5E-04	5.0E+06	1.2E+03
		0.00010%	10-30 Todesopfer	2.20E-07	15	3.9	1.3E-05	5.0E+06	6.4E+01
		0.00001%	> 30 Todesopfer	2.20E-08	35	5.9	4.6E-06	5.0E+06	2.3E+01

Figure 18: Example of the event tree for collisions, case study, Section 1, damage indicator “Fatalities”

5.3 Scenario type “Fire without hazardous goods according to the ADR”

Table 14 summarises the most important factors for determining the event frequencies and extents of damage for the scenario type "Fire":

Branching point of event tree	Comments
[1] Initial event "Fire"	The frequency of the initial event "Fire", i.e. the probability that a fire with at least 5 MW thermal power occurs, is 0.032 fires per year for the tunnel. This frequency includes the frequency of a fire as a result of a collision (0.007 fires per year) and the frequency of a fire as a result of a technical fault (0.025 fires per year).
[2] Accident site	Given a tunnel length of 704 m and the assumption that each portal area has a length of 100 m (200 m per tunnel), a distribution of 28% to 72% results.
[3] Flowing traffic / tailback	It is assumed that there are 250 tailback hours per year. The conditional probability that a fire happens at the time of a tailback can therefore be estimated at 3%.
[4] Detection / ventilation	A total failure rate of 1% is assumed.
[5] Thermal power	- 5 MW: 90.00% - 30 MW: 9.90% - 50 MW: 0.09% - 100 MW: 0.01%
[8] Model value for extent of damage	Fire simulations with FDS (Fire Dynamic Simulator) were performed for selected cases to estimate the extent of damage.[26] FDS allows mapping the geometrical conditions of the tunnels, the effects of the fire ventilation, the thermal power and the initial conditions relevant for the spreading of the smoke gas (e.g. traffic flow or tailback). The procedure described for considering self rescue (as a function of the site-specific escape options) was used to determine the resulting number of fatalities. The following values were assumed for estimating the fatalities as a function of the self-rescue conditions: - No self-rescue: 100% fatalities - Conditional self-rescue: 30% fatalities - Self-rescue: 5% fatalities - Safe area: 0% fatalities Figure 19 shows an example for determining the number of fatalities based on the spreading of smoke gas simulated with FDS. The procedure is described under *Branching point 8*.

Table 14: Branching points of the event tree for fire, case study

[26] Modelling and calculation of individual sub-scenarios with FDS requires relatively high effort. For this reason, the extent of damage for a part of the sub-scenarios was derived from the model values determined by using conclusions by analogy/estimates.

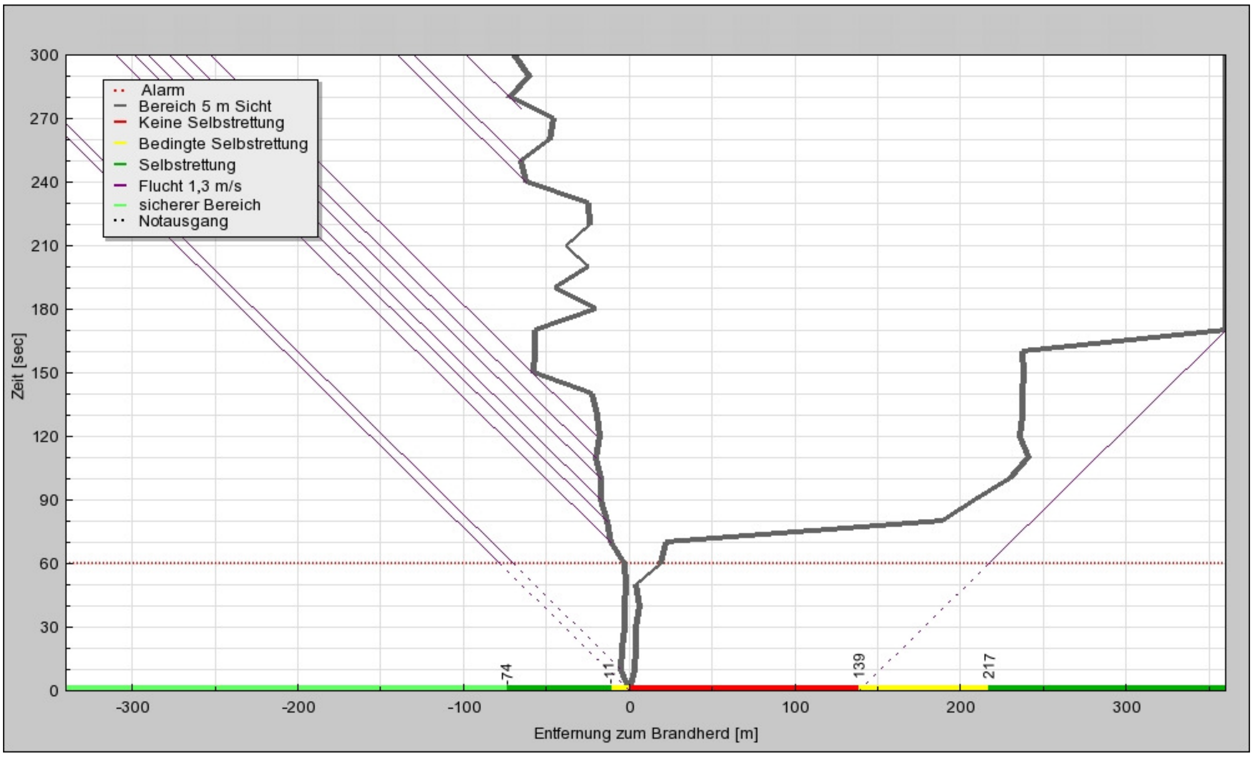

Figure 19: Example for determining the extent of "Fatalities" (situation: Section 1, free traffic flow, 30 MW fire, with ventilation)

5.4 Results

The risks determined by the present method where used to estimate the following expected extent of damage:

- The collective risk (expected extent of damage) for collisions with regard to the damage indicator "Fatalities" is 0.02 fatalities per year. Statistically, a collision with one resulting fatality can be expected in Tunnel A every 50 years.
- The collective risk (expected extent of damage) of fire events with regard to the damage indicator "Fatalities" is 0.002 fatalities per year. Statistically, a fire with one resulting fatality can be expected in Tunnel A every 500 years.
- The monetarised risk R_m is approx. € 245 000.- per year and is primarily determined by the damage indicator "Fatalities" (approx. € 175 000.- per year). The main part of approx. 80% is due to the scenario type "Collision".

Figure 20 below shows the determined, standardised cumulative curves. The resulting total cumulative curve has the following characteristics:

- In the range of small extents of damage (up to approx. 10 fatalities) the impact of the scenario type “Collision” dominates. This is due to the fact that these events are clearly more common than fires.
- In the range of extents of damage between 10 and approx. 30 fatalities, the impact of both scenario types is approx. equally important for the shape of the total cumulative curve.
- In the range of large extents of damage, the scenario type “Fire” determines the shape of the total cumulative curve. The maximum extent of damage is typically determined by the scenario type “Fire” due to the large impact area of fires (spreading of smoke gas).

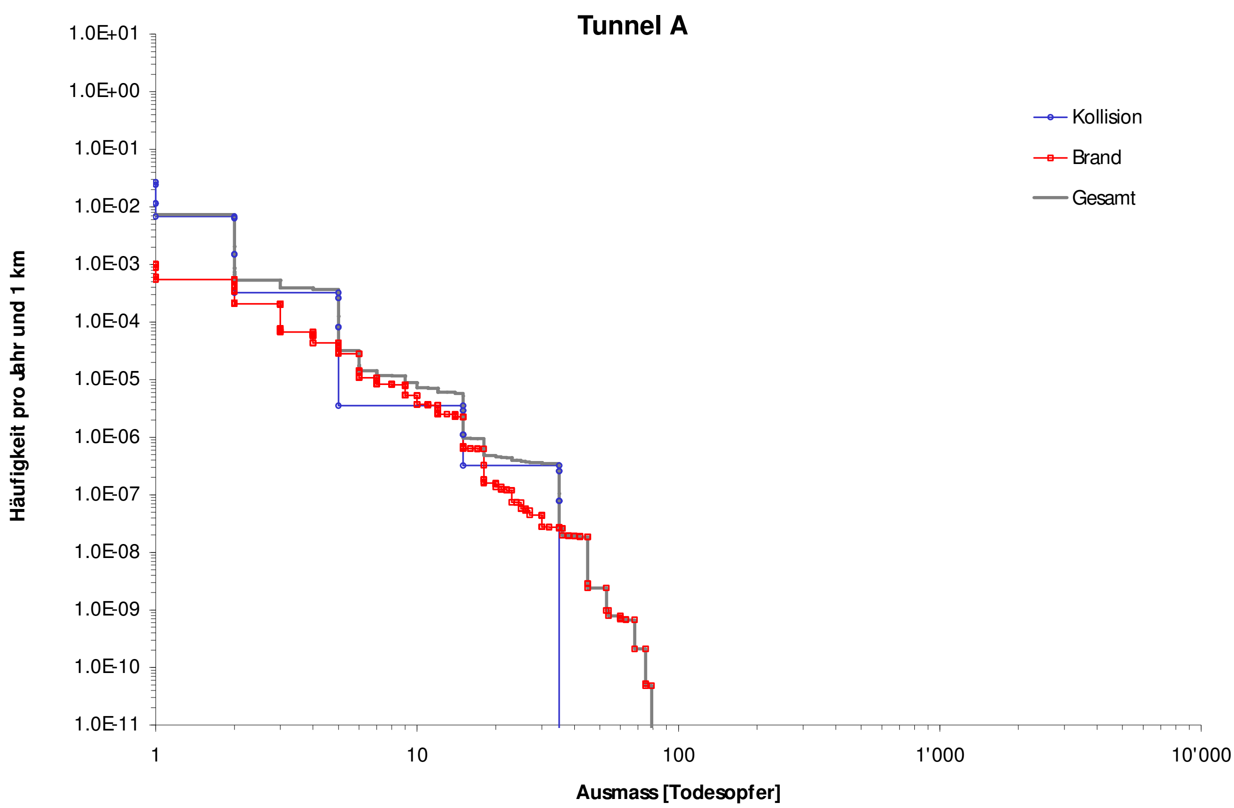

Figure 20: Standardised cumulative curves for the case study “Tunnel A”

6 Conclusion and summary

Fire events during the last years in various European road tunnels have intensified the discussion about safety and the efforts for further risk reduction. The requirements in the directives RABT 2006 and 2004/54/EG show that risk-oriented approaches become increasingly important for regulatory stipulations. In contrast to the measure-oriented approach, they facilitate consideration of specific tunnel characteristics in the planning of safety measures.

The present method provides solutions with regard to the requirements for a risk-oriented approach in the directive RABT 2006 and 2004/54/EG. It creates a basis for a standardised and comparable execution of safety evaluations. During the development of the method, experience with other, comparable safety areas was considered and appropriate approaches were investigated for their suitability in the present context. Current developments and systematic approaches abroad for implementing the requirements in Article 13 of the directive 2004/54/EG were analysed and useful findings were included in the development of this method. The methods and procedures of the present suggestion are based in a risk-oriented approach that is already successfully used in several countries for a wide range of safety issues.

During the development of the method, care was taken that the approach selected was based on scientific principles and that it was practically oriented, considering future applications. Recipe-type specifications for all aspects were deliberately avoided. The method rather provides a framework in which the specific application has to be performed. Given the variety and complexity of current tunnel constructions, the associated infrastructures and the resulting interactions, the focus is on stipulating the essential principles with regard to methods. The user must have an opportunity for considering the specific characteristics of a tunnel within these specified limits.

The suggested method for safety evaluation is based on a quantitative analysis of the risks and allows for consideration of the major, risk-relevant factors. The quantification requires some assumptions, as appropriate basic data and statistical information are not always available. This quantitative approach makes it possible to document the assumptions made in a transparent manner. If comprehensive data become available at a later stage, individual factors or their quantitative values can be adjusted, if required, without the need to change the basic principles of the procedure. A future improvement of the estimates for event frequencies requires that the accident analysis that was conducted as part of this research project is continued and extended.

The actual risk analysis provides information concerning the level of the risks, while the risk evaluation provides statements concerning their acceptability. It is basically assumed that a tunnel conforming to the directives can be classified as safe. The risks of a planned tunnel that does not comply with the requirements of the directives must therefore be compared with those of a comparable tunnel that complies with the directives. However, this measure-oriented approach does not define a uniform safety level, as different tunnels will pose different risks, even if they all comply with the directive. It is therefore recommended to pursue the suggested approach of defining a quantitative safety goal (acceptability ranges in the damage frequency diagram). It is further suggested that additional plans for safety measures are evaluated with regard to cost-effectiveness.

7 Recommendations for the set of regulations and further research requirements

The suggested method stipulates the procedure for the safety evaluation of road tunnels and the associated principles. Based on the findings in this research project, the following recommendations can be made with regard to further development of the set of regulations:

- *Basic data:* The evaluation of accidents provides an important basis for the quantification of risks. It is recommended to extend the existing basic data and to continue with the statistical evaluation. This will provide a more reliable basis for future risk analyses and might reveal further, relevant factors.
  The accident analysis performed as part of this project showed that the information collected for an accident is partially insufficient for risk analysis purposes. The information concerning the place is often inaccurate and/or not plausible or information concerning the concomitant circumstances of the accident is not available. One of the purposes of quantitative risk analysis is the identification of the various factors and their interactions. It would therefore be desirable if future evaluations of accident events could draw on specific information that allows better mapping of events in the risk analysis and the basic statistical data. It would, for example, be of considerable help if kilometre markers were attached to each tunnel block, which would make spatial allocation much easier.
  In contrast to accident events, systematic evaluations of operational failures and technical faults in the tunnel infrastructure are hardly performed nowadays. It would be desirable if such basic data could be collected in future. Such information would not only aid risk analysis, but would also be useful for maintenance planning of systems, etc.
- *Evaluation criteria:* It is recommended to pursue the suggested approach of a standardised, absolute evaluation criterion. An evaluation that is only based on a relative comparison with a tunnel complying with the directive seems insufficient from the point of view of the investigator, as it creates a uniform equipment standard but not a uniform, minimum safety standard. It would be preferable to determine an absolute risk evaluation criterion that

stipulates a uniform minimum safety level. It is further suggested that additional plans for safety measures are evaluated with regard to cost-effectiveness.

- *Risk analysis for transports of hazardous goods:* According to RABT 2006, risk analyses have to be performed for all tunnels before permitting the transport of hazardous goods. Appropriate methods are available (OECD/PIARC model and equivalent, other models). It is suggested to initiate an investigation to determine to what extent the results of these models are consistent and what adjustment of the results might be required to make them comparable.
  It is now common practice that risk analyses for hazardous goods do not only consider a tunnel in isolation but compare the risks of a route with tunnels with a possible alternative route. However, practical specifications concerning the method of risk evaluation (comparison of cumulative curves in the damage frequency diagram, collective risks, etc.) are not yet available. Appropriate specifications should therefore be developed.
- *Evaluation of experiences with risk analyses*: It is recommended to collect and evaluate the experiences gained during the performance of risk analyses in a systematic manner.