Risk Analysis for Road Tunnels

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PIARC Technical Committee 3.3 - Working Group 2
“Management of Road Tunnel Safety”

The PIARC Working group No. 2. ‘Management of Road Tunnel Safety’ of Technical Committee 3.3 on Road Tunnel Operation, aims to provide safer tunnels by:

1. The development of an integrated approach of road tunnel safety. This includes a holistic approach, a survey of prescriptive versus performance-based criteria, and a choice of measures for new and in-service tunnels.
2. Studying the application of risk analysis. This will cover the principles and use as well as a survey of methodical elements of risk analysis, a short presentation of selected methodologies (including case studies), and an overview of experience and practical application of risk analysis methods in diverse countries.
3. The promotion and follow-up use of OECD/PIARC QRA and DSM software. This includes the promotion, assistance in distribution, advice on support and training, follow-up of use and improvements, advice on policy implications.
4. The responsibilities in tunnel safety management (definition of responsibilities, tasks, competences, organisation, relations between bodies, procedures to verify the safety of tunnels).
5. The development of tools for safety management (safety documentation, collection and assessment of incident data, safety inspections).

Five subgroups were initiated in Lyon in September 2004 in order to realize these aims.

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Members of Subgroup 2 and Authors of the present Report

This document is a report on risk analysis methodologies to be adapted in the risk assessment process for road tunnels. It is the documentation of the work of subgroup 2 which consists of the following members (in alphabetic order), who contributed all to the present report:

Massimo Guarascio (Person in charge - Italy)
Nelson Goncalves (France)
Robin Hall (UK)
Jelle Hoeksma (the Netherlands)
Milan Holicky (Czech Republic)
Bernhard Kohl (Austria)
Philippe Pons (France)
Athanasios Saramourtsis (Greece)
Christoph Zulauf (Switzerland; corresponding member representing Germany)
Context of the Work of Working Group 2
“Management of Road Tunnel Safety”

Risk Awareness

The recent history of tunnel disasters shows that the frequency of accidents in tunnels is high. The likelihood of escalation of these accidents into major events is low, however the consequences of such accidents can be severe in terms of victims, damage to the structure and impact on the transport economy.

More specifically, the recent catastrophes of the Mont Blanc tunnel, the Tauern tunnel, Kitzsteinhorn tunnel and St. Gothard tunnel have demonstrated the urgent need for improving the prevention dealing with tunnel accidents, namely by adequate detection systems and preparedness of operation staff and emergency services.

This can be achieved by providing safe design and construction criteria for new tunnels, re-organizing the management and the configuration of in-service tunnels, provide management with proper decision support safety tools, follow-up the state of safety in tunnels and through improved information and better communications with tunnel users. This was clearly outlined in the recommendations issued by an international committee in charge of investigating the Mont-Blanc catastrophe [13]. Conclusions were that fatal consequences could be greatly reduced by a more efficient organization of emergency services (harmonised, safer and more efficient emergency procedures for cross-border operations), more skilled personnel, more powerful safety systems and by higher awareness among users (car and truck drivers) on how to behave in emergency situations.

The reaction of politicians and the tunnel community

Since 1999 road tunnel safety has been a subject of growing interest, thanks to that risk awareness that was raised by the different incidents. The numerous initiatives, which have taken place at the national, European and international levels, have led to different regulatory developments (see details in WG2/Sub Group 1 report “Integrated Approach to Road Tunnel Safety”).

The European Directive 2004/54/EC (named European Directive) is today the major legislative text to be issued at such a huge level.
Also PIARC (the World Road Association) is an international forum for analysis and discussion of the issues related to road tunnel safety, identifying, developing and disseminating best tunnel safety management practice and giving better access to international information with regard to tunnel safety. One of the themes in the strategy of PIARC is the improvement to safety assessments, mechanisms, design and procedures consistent with efficient and effective operations that meet road user. One of the goals is to improve the safe and efficient use of the road system, taking into account road structures such as tunnels, including the movement of people and goods on the road network, while effectively managing the risks associated with road transport operations and the natural environment.
1. Introduction

1.1 What is risk analysis and what can be accomplished by using risk analysis?

In general risk analysis is a risk assessment tool which initially has been developed to investigate safety of potentially dangerous industrial processes (e.g. in the chemical industry) or potentially dangerous industrial plants (such as nuclear power plants). The application of risk analysis should help to establish a proactive safety strategy by systematically investigating potential risks. This proactive safety strategy was to replace merely experience-based concepts mainly relying on findings from incidents or accidents, that had already happened. During the past 15 years some risk analysis methods have been adapted to the investigation of tunnel safety in general and road tunnel safety in particular.

Very generally spoken, risk analysis deal with potential negative consequences of a technical system in the future and – as nobody is able to predict future events – the only option in such a situation is to develop - as realistic as possible - a model of the risks associated to the system in question (14). As basically exists an unlimited number of possibilities how dangerous effects may develop it is theoretically impossible to take all possible situations into account; therefore it is inevitable to restrict any investigation to a limited number of selected representative scenarios, thus always including the possibility, that important scenarios are lacking or that too much emphasis is put on effects of minor importance. For that reasons it should always be kept in mind that every kind of risk analysis – whatever method is used - is a more or less simplifying model relying on preconditions and assumptions and is not a copy of reality. Nevertheless risk analysis provide a much better understanding of risk-related processes than merely experience-based concepts ever may achieve.

The meaning of risk analysis and its characteristics can be summarized as follows:

- Risk analysis is a systematic approach to analyse sequences and interrelations in potential incidents or accidents, hereby identifying weak points in the system and recognising possible improvement measures
- The term “Risk Analysis” covers a big family of different approaches, methods and complex models combining various methododical components for specific tasks
- Risk analysis makes the quantification of risks feasible thus establishing the basis of a performance-based approach for the assessment of safety standards
A general basic principle of all kinds of risk analysis for road tunnels should be a holistic approach including infrastructure, vehicles, operation and - last but not least - users (fig 1).

Figure 1: Holistic approach for risk analysis

Risk analysis can be used
- to check general consistency of safety planning
- to choose between alternatives
- to demonstrate that safety standards are fulfilled, eg. in case of deviations from prescriptions
- to optimize safety planning in terms of cost-effectiveness

1.2 Objectives of the document

The main objectives of the document have been defined as follows:
- provide a general description of risk analysis as a useful tool for the risk assessment process of road tunnels
- give a definition of important terms related to risk analysis and the risk assessment process
- prepare a survey of different methods used for the risk assessment of road tunnels in various countries, their range of application and their specific characteristics
- collect and evaluate practical experience and ensure an exchange of experience with different countries
- identify problems and find solutions
- discuss results and draw conclusions
- identify need for further investigations
1.3 Working process

For the development of the present document a specific working process was developed:

- Collection of experience in application of risk analysis in PIARC member states (by distributing questionnaires and evaluating the answers)
- Collection and analysis of existing methods and/or methodology components based upon the preliminary results of EU-funded research projects (mainly SafeT) and own investigations (see step 1)
- Description of a limited number of practically applied methods including information on range and limits of application based upon the practical experience and knowledge of members of the working group
- Documentation of a case study for each method described provided by members of the working group
- Discussion of relevant results and findings in the working group and deduction of conclusions and recommendations

1.4 Target audience

This document addresses a target and audience at two different levels: on the one hand it is dedicated to risk analysts, who can find in the document detailed explanations of the different risk analysis procedures adapted and implemented by the different countries which participate to the PIARC group, and on the other hand to tunnel engineers in general who, even if were not specialists in this field, can catch the philosophy of risk analysis for road tunnel safety in the general descriptions of the document as well as in the case studies presented in chapter 5.

1.5 A brief summary of the document

The document is structured according to the following topics:

- Chapter 2 presents a brief review of the general principles and basic terminology to be adapted for the implementation of a risk based safety assessment in the risk management process. The proposed glossary of terms is consistent with the main available national standards and valid international documents provided by the International Standard Organization ISO. In addition results of a new working group (established recently within technical committee ISO/TC98, subcommittee SC2), which is responsible for developing a standard on the Risk Management of Civil Engineering Systems, are considered.
- Chapter 3 deals with different types of methodologies of Risk Analysis for road tunnels presented and discussed at two different levels of complexity: in a first step general component methodologies are presented in a systematic order and in a second step selected practical methods for the risk assessment of road tunnels are discussed, referring to the components presented in step one.
• Chapter 4 provides an overview of the existing methods, used and/or implemented in different countries. The comparison among them is obtained by evaluating questionnaires from different countries. The original questionnaires will be published in a separate document at PIARC-website. In particular the response of different methods to the requirements stated by the European Directive 2004/54/CE will be detailed.

• Chapter 5 is devoted to present seven risk analysis case studies from different countries (Austria, France, Great Britain, Italy, The Netherlands (two examples), DG QRA model) developed according to the different practical methods presented above.

• In Chapter 6 conclusions are drown especially on the nowadays limitations in the applicability of risk models together with recommendations derived from practical experience.
2. General principles and terminology

2.1 Implementation of risk assessment in the risk management process

Harmonization of general principles and terminology used in the risk management of tunnels and other of civil engineering systems is of uttermost importance. Currently risk assessment is becoming a common tool for verification of tunnel safety in several countries. Risk analysis is explicitly requested (if necessary) by recent Directive of the European Parliament and of the Council (2004). Moreover, the general principles and basic terms used for tunnels should be consistent with those used for other civil engineering systems. Then an effective risk communication between responsible partners, which seems to be an indispensable and extremely important part of risk management, can be established. Thus, a harmonization of general principles and terminology of the risk analysis is needed.

General principles and terminology given below are based on available national standards and valid international documents provided by the International Standard Organization ISO (documents [1] to [11]). In addition materials of a working group WG 11 of the technical committee ISO/TC98, subcommittee SC2, which is responsible for developing a standard General Principles on Risk Assessment for Structures, are considered.

2.2 Elements of risk based safety assessment

The main components of risk management and relevant basic terms are indicated in a simplified diagram in Figure 2 (based on document [10]).

![Figure 2](image)

**Figure 2** A framework for risk management (adopted from [10]).

Figure 2 shows that the whole process of risk management includes the risk assessment and risk control. Risk assessment consists of risk analysis and risk evaluation. Figure 2 also indicates one type of risk communication providing, in that case, an unavoidable exchange of data between the
risk assessment and risk control. Obviously other types of risk communication may be required in case of risk management of complex tunnel systems.

A simplified flowchart of risk assessment, consisting of risk analysis and risk evaluation, is shown in Figure (adopted from [7]).

![Flowchart of iterative procedure for the risk assessment](image)

**Figure 3** Flowchart of iterative procedure for the risk assessment (adopted from [7]).

It should be noted that Figure and Figure show the main typical components of the risk management only; more detailed diagrams, supplementary components and additional mutual links may be needed when analysing safety of a particular tunnel.
2.3 Terminology

Considering the main area of their application the terms defined below are subdivided into four groups:

- general terms,
- terms related to risk communication,
- terms related to risk assessment,
- terms related to risk management and control.

It is expected that additional terms or their more detailed definitions may be needed in complex cases. The list of the terms may be supplemented by additional items, definitions or notes when needed.

A special attention requires the terms “risk” and “safety”. In a general sense, both terms are sometimes used as synonyms, sometimes as complementary terms. For example the collocations “risk analysis” and “safety analysis” are often used to describe the same topic. In a narrow technical sense the terms “risk” and “safety” may have complementary meaning: “safety” is a state with limited consequences, i.e. with a limited (tolerable) “risk” (see the definition 2 in Section 2.3.1). However, in a broad area of risk management the term “safety” commonly covers a greater set of factors than the term “risk” (see note 1 of the definition 2 in Section 2.3.1). Note that in structural reliability the term “safety” is often understood as “reliability” (see note 2 of the definition 2 in Section 2.3.1.).

2.3.1 General terms

1. **System**: A group of interrelated, interdependent or interacting elements forming an entity, which is capable to reach a given objective through the interaction of its parts.

   Note 1: This definition implies that the system is identifiable and is made up of interacting elements or subsystems, which are identifiable. Moreover the boundary of the system must be explicitly defined [10].

   Note 2: In terms of technological hazards, a system is normally constituted by a physical subsystem, a human subsystem and a management subsystem; the environment in which the system is embedded is also important [10].

2. **Safety**: The ability of a system to resist hazards without inadequate consequences.

   Note 1: Sometimes in risk assessment safety is understood as the complementary term to the risk (see the definition of Risk); indeed it should be regarded as the counterpart of damage or unutility (see the definition of Consequence) measuring the grade of fatalities and injuries associated to a given event. In addition to direct consequences other factors affecting the tunnel safety are the evacuation time or the access time period.
Note 2: In structural reliability safety is often understood as reliability with respect to the ultimate limit state (see the definition of Reliability).

3. **Hazard**: A state of the system which is a potential for undesirable consequences.

Note 1: For instance a non-standard demand requirement and/or an insufficient supply capacity or an excessive deviation from design dimensions, in the case of a chemical, the potential that the substance has for causing adverse effects at various levels of exposure.

Note 2: In some documents (for example in the recent draft of EN 1990 [1]) the hazard is defined as an event, while in risk analysis [10] it is considered as a condition with a potential for causing an event. Thus in risk analysis hazard is a synonym to danger.

4. **Hazard identification**: A process to recognise hazards and define its basic characteristics.

5. **Event**: Occurrence of a particular set of circumstances.

Note: An undesired event is an event, which causes negative consequences like human fatalities and injuries or environmental damage and economic losses.

6. **Hazard scenario**: A sequence of possible events coming out from a given hazard leading to undesired consequences.

Note: To identify what might go wrong with the system or its subsystem is crucial to a risk analysis. It requires the system to be examined and understood in considerable detail.

7. **Scenario** (associated to a given initial event) A sequence of possible events coming out from a given initial event and associated to a special behaviour of the different subsystems.

Note: It is not mandatory to associate only undesired consequences to every scenario; as matter of facts starting from a given initial event every admissible path can be drawn by the elements of the system.

8. **Probability**: A measure of the chance or degree of belief of a particular event occurring within a specified reference (time, number of repetitions, etc.).

Note: The probability may significantly depend on the time period during which the particular event may occur.

9. **Objective probability**: The probability determined using theoretical arguments or adequate statistical data.

10. **Subjective probability**: The probability determined using intuition and relevant experience.
11. **Consequence:** The utility assigned to a scenario or a sequence of events in accordance with the preferences of the decision maker; apparently the considered scenario can reduce to only one event.

   **Note 1:** There can be more than one consequence from one event.

   **Note 2:** Consequences can range from positive to negative.

   **Note 3:** Consequences can be expressed qualitatively or quantitatively.

12. **Risk:** The expected consequences associated with an activity. Risks may be related to adverse events for humans, qualities of the environment or economic values.

   **Note 1:** Risk is often estimated by the mathematical expectation of consequences of an undesired initial event. Therefore it is evaluated by the summation of the products "probability × consequences" associated to the complete set of admissible consequences coming out from the undesired initial event. A more general interpretation of risk can involve probability and consequences in a non-product form. This presentation is sometimes useful, particularly when a spectrum of consequences, with each having its own corresponding probability of occurrence, is considered.

   **Note 2:** The term "individual risk" is often used to denote the risk related to a particular person (usually expressed as a probability to be injured or killed), the term "societal risk" is used to denote the risk relevant to a society (usually expressed as expected number of fatalities or by F-N curve).

   **Note 3:** Various levels of risk may be recognised, for example acceptable risk, tolerable risk and objective risk (see the definition of these terms).

13. **Objective risk:** An estimate of the risk, associated to a given set of triggering in initial events, obtained using theoretical arguments, adequate statistical data (for example the annual expected fatalities from car accidents) or quantitative risk analysis methods (QRA, PRA).

14. **Reliability:** The ability of a structure or structural element to fulfil the specified requirements during a given period of time (e.g. design life).

   **Note 1:** reliability is often expressed as a probability related to a specific requirement and a period of time [1, 2].

   **Note 2:** With respect to ultimate limit states, reliability is often referred to as safety, with respect to serviceability limit states, reliability is often referred to as serviceability [1, 2].
2.3.2 Terms related to risk assessment

1. **Risk assessment**: A process of risk analysis, risk acceptance, and option analysis.
   
   Note 1: The entire risk assessment is schematically indicated in Figure 2 (adopted from [10]) and Figure 3 (adopted from [7]).

   Note 2: In some documents [1] risk assessment matches risk analysis and risk evaluation, where risk evaluation covers risk acceptance and option analysis (see the definition of risk evaluation).

2. **Probability analysis**: A systematic procedure for describing and/or calculating probabilities of subsequent desired or undesired events.
   
   Note: In risk assessment the probability analysis is often done using an event tree scheme.

3. **Causal analysis**: A systematic procedure for describing and/or calculating the probability of causes for desired or undesired events.
   
   Note: In risk assessment the causal analysis is often done using a fault tree scheme.

4. **Consequence analysis**: A systematic procedure to describe and/or calculate consequences.

5. **Risk analysis**: The use of available information concerning relevant hazard situations, probability of critical initial events, reliability of the subsystems and quantitative scenario analysis for estimating the level of risk for individuals or populations, property or environment.
   
   Note 1: Quantitative Risk Analysis (QRA) is commonly used term describing an analysis the provides quantitative information enabling decision on the acceptability of risk.

   Note 2: Risk Analysis generally involves context (scope) definition, hazard identification, and risk estimation [10].

   Note 3: The entire risk analysis is schematically indicated in Figure 3 (adopted from [7]).

6. **Risk estimation**: A process used to produce the estimate of the risk measure.
   
   Note 1: The risk estimation is based on hazard identification and generally contains the following steps: scope definition, probability analysis, consequence analysis, and their integration [10].

   Note 2: The entire risk analysis is schematically indicated in Figure (adopted from [10]) and Figure (adopted from [7]).

7. **Risk evaluation**: A process of risk acceptance and option analysis.
8. **Sensitivity analysis**: A systematic procedure to describe and/or calculate the effect of variations in the input data and underlying assumptions on the final result.

9. **Option analysis**: A process used to identify a range of possible alternatives for managing the risk.

### 2.3.3 Terms related to risk communication

1. **Risk communication**: The exchange or sharing of information about risk between the decision-maker and other stakeholders.
   
   Note 1: The information can relate to the existence, nature, form, probability, severity, acceptability, treatment or other aspects of risk.
   
   Note 2: One important type of risk communication is schematically indicated in Figure 2 (adopted from [10]).

2. **Stakeholder**: Any individual, group or organization that can affect, be affected by, or perceive itself to be affected by risk [8].
   
   Note 1: The decision-maker is also a stakeholder.
   
   Note 2: The term “stakeholder” includes but has a broader meaning than the interested party (which is defined in ISO 9000:2000).

3. **Interested party**: A person or group having an interest in the performance or success of an organization [7].
   
   Examples: Customers, owners, people in an organization, suppliers, bankers, unions, partners or society.
   
   Note: A group can comprise an organization, a part thereof, or more than one organization (ISO 9000: 2000, definition 3.3.7).

4. **Risk perception**: The way in which a stakeholder views a risk, based on a set of values or concerns [7].
   
   Note 1: The risk perception depends on the stakeholders' needs, issues, knowledge and preferences.
   
   Note 2: The risk perception can be significantly subjective.

5. **Criteria of risk**: The reference points against which the results of the risk analysis are to be assessed. The criteria are generally based on regulations, standards, experience, and/or theoretical knowledge used as a basis of the decision on acceptable risk.
Note: Various aspects may be considered, including cultural, social, psychological, economic and other aspects. The acceptance criteria may be expressed verbally or numerically.

6. **Acceptable risk**: A level of risk, which is generally not seriously perceived by society, and which may be considered as a reference point in criteria of risk.

   Note: It is expectable that various aspects including cultural, social, psychological, economic and other aspects will influence the risk perception in society (see also the definition of risk criteria).

### 2.3.4 Terms related to risk management and control

1. **Risk management**: The complete process of risk assessment and risk control.

   Note: The entire risk management is schematically indicated in Figure 2 (adopted from [10]).

2. **Risk control**: Actions implementing risk management decisions.

   Note: The risk control may involve monitoring, reevaluation, and compliance with decisions. The entire risk control is schematically indicated in Figure 2 (adopted from [10]).

3. **Risk treatment**: A process of selection and implementation of measures to modify risk [9].

   Note 1: The risk treatment is schematically indicated in Figure 3 (adopted from [7]).

   Note 2: The term “risk treatment” is sometimes used for the measures themselves.

   Note 3: The risk treatment measures can include avoiding, optimizing, transferring or retaining risk.

4. **Safety management**: A systematic process undertaken by an organisation in order to attain and maintain a level of safety that complies with the defined objectives.

5. **Tolerable risk**: A level of risk which an individual or society is willing to accept to secure certain benefits assuming that the risk will be properly controlled.

   Note: The tolerable risk may not be negligible, but it should be kept under review and permanent control.

3. **Risk optimization**: A process, which tends to minimize the negative and to maximize the positive consequences and their respective probabilities [8]. Risk optimization works on prevention, protection and mitigation of consequences.

   Note 1: In the context of safety, risk optimization is focused on risk reduction.
Note 2: Risk optimization depends upon risk criteria, including costs and legal requirements.

Note 3: A risk associated with risk control can be included.

7. Risk reduction: Actions taken to lessen the probability, negative consequences, or both, associated with a given level of risk [7].

8. Mitigation: Limitation of any negative consequence of a particular event [8].

9. Risk avoidance: The decision not to become involved in, or action to withdraw from a risk situation.
   Note: The decision may be taken based on the result of risk evaluation.

3. Risk transfer: Sharing with another party the burden of loss or the benefit of gain, for a risk [7].
   Note 1: Legal or statutory requirements can limit, prohibit or mandate the transfer of a certain risk.
   Note 2: The risk transfer can be carried out through insurance or other agreements.
   Note 3: The risk transfer can create new risks or modify existing risk.
   Note 4: Relocation of the source is not the risk transfer.

11. Risk financing: Provision of funds to meet the cost of implementing risk treatment and related costs [7].
   Note: In some industries, the risk financing refers to funding the financial consequences related to the risk only.

3. Risk retention: Acceptance of the burden of loss, or the benefit of gain, from a particular risk [7].
   Note 1: The risk retention includes the acceptance of risks that have not been identified.
   Note 2: The risk retention does not include treatments involving insurance, or transfer by other means.
   Note 3: There can be variability in the degree of acceptance and dependence on risk criteria.

3. Risk acceptance: The decision to accept a risk.
   Note 1: The verb “to accept” is chosen to convey the idea that acceptance has its basic dictionary meaning.
   Note 2: The risk acceptance depends on risk criteria.
14. **Residual risk**: A risk remaining after risk treatment [8].


3. **Methodologies of Risk Analysis**

3.1 **Overview of component methodologies**

This chapter will give a short overview about the most important aspects and methodical components that are used in general for risk assessment. Risk assessment procedures are explained in chapter 3.1 and their practical application for road tunnels in chapter 3.2.

### 3.1.1 Components of Risk Assessment

For the process of risk assessment of road tunnels, a vast choice of methodology components is available. Figure 2 illustrates the main steps of risk assessment: risk analysis and risk evaluation. The results will be affected by (additional) safety measures. Therefore the following three steps of risk assessment are distinguished:

1. **Risk analysis**: Risk analysis is concerned with the fundamental question: “What might happen and what are the consequences?”. Risk analysis can be carried out in a qualitative or in a quantitative way or in a combination of both. In case of a quantitative analysis probabilities of accidents and their consequences for different damage indicators (e.g. in terms of fatalities, injuries, property damage, interruption of services) and the resulting risk are estimated.

2. **Risk evaluation**: Risk evaluation is directed towards the question of acceptability and the explicit discussion of safety criteria. For a systematic and operable risk evaluation one has to define safety criteria and to determine whether a given risk level is acceptable or not. In other words risk evaluation has to give an answer to the question “Is the estimated risk acceptable?”

3. **Planning of safety measures**: If the estimated risk is considered as not acceptable, additional safety measures have to be proposed. Therefore the effectiveness and also cost-effectiveness of different safety measures can be determined by using the initial frequency and consequence analysis of the scenarios which will be positively or negatively affected under the assumption that the investigated safety measure has been implemented. Planning of safety measures has to answer the question “Which measures are necessary to get a safe (and cost-efficient) system?”

### 3.1.2 Risk analysis methodology components

A broad spectrum of qualitative or quantitative methodology components exists for each step of the procedure of risk assessment as described. Figure 4 shows an overview of the applicable
methodology components for the three steps of risk assessment. Further information about the most important components and the most often applied methodologies are summarised in Appendix 1.

Figure 4: Overview of methodology components for risk assessments [12] [13]
The available methodical components can be arranged roughly into two groups: *Qualitative components* normally have a lower complexity than quantitative and are based on the application of arbitrarily definable evaluation standards. Qualitative methods are often simple and easily and flexibly applicable and can be used for almost every problem (even in situations, where no quantitative data is available). On the other hand there is the risk that too much weight is put on subjective impressions and that correlations of different elements of the analysed system are not (or not in a sufficient way) taken into account.

*Quantitative components* try to structure possible events of a system in a logical and integrative way: Different scenarios and possible subsequent events are analysed and the relevant influences are identified. For each path of subsequent events the scenario-specific frequency and consequences are estimated. The measured variables, which affect the development of a specific event, are identified and the appropriate risk is determined. A substantial advantage of using quantitative methods is the transparent representation of the risk estimated, whereby a better understanding of complex correlations can be achieved. On the other hand there are problems which cannot be modelled in an adequate way (with reasonable resources of time and money) and it also may happen, that not sufficient quantitative data is available to enable a proper quantification of the most important parameters. Quantitative approaches are often characterized by a high degree of complexity, which reduces their comprehensibility as well as their controllability.

In addition, risk-based approaches can also be partitioned into the following two types of approaches:

- **Scenario-based approach**: The frequency and/or the consequences of an event are estimated and the possible resulting consequences for a specific scenario are analysed. The risk assessment is done separately for each single scenario on the basis of their characteristic risk values.

- **System-based approach**: By applying a system-based approach, risk values for an overall system are estimated. Thus all events/scenarios, which can affect persons in the system considered, are taken into account.

Methodology components can be specified for the three steps risk analysis, risk evaluation and planning of safety measures:

- **Risk analysis**: Often, for the risk analysis, different methodology components are being combined. In practical applications this is usually necessary, because of lack of data.

- **Risk evaluation**: Usually evaluation methodology components can only be combined in a limited way.
Planning of safety measures: The choice of the methodology components is closely connected to the evaluation methodologies applied.

By combining the methodology components for risk analysis, risk evaluation and planning of safety measures a complete procedure for risk assessment is developed. But the different components are not arbitrarily combinable. Certain evaluation methodology components need certain analysis components. Furthermore the evaluation of measures is also closely coupled to the evaluation methods.

The application of the different methodology components in a complete procedure for risk assessment is different depending on specific requirements, the complexity of the analysed system and the specific application. When using quantitative methods, commonly different methodology components are combined. It is often difficult to clearly identify the methodology components used because of the use of combinations. Increasing complexity of the systems (e.g. nuclear plants, chemical industry or traffic systems) strengthens the use of quantitative methods such as logical trees, simulations or spread and effect models. Many quantitative procedures rely on statistical records, often in combination with expert judgments needed to make up for lacks in the data bases.

The experience in handling risk assessments shows, that for some applications (such as comparison of different design features, comparison of different safety measures, cost-effectiveness-analysis of safety measures) the use of quantitative methods is practically preferable for system-spreading safety evaluations. By using quantitative methods, comparable evaluations can be ensured. For such applications the integrated approach, quantitative comparability and in some cases also comprehensibility are the most important advantages of system-based quantitative approaches. Simple qualitative methods, as for instance “expert judgments”, often do not keep the two components risk analysis and risk evaluation sufficiently apart. On the other hand, scenario-based approaches are well suited for a detailed time-related analysis of sequences of events, which for example allows a realistic planning of emergency response measures.

For the purpose of risk evaluation several different types of risk criteria are available, which – once again – cannot be chosen arbitrarily but depend on the methodology components having been used for risk analysis.

The following types of risk criteria can be adopted:

- expert judgement (subjective, qualitative)
- prescriptive standards or guidelines (objective, qualitative)
- scenario related criteria - such as: threshold values for scenario probabilities; escape time to a safe area; access time of rescue services; (semi-objective, quantitative)
– individual risk – probability to be injured/killed per year of one specific person exposed to a risk (semi-objective, quantitative)

– societal risk – expected value; expected number of fatalities in the tunnel per year (semi-objective, quantitative)

– societal risk – F-N curve; P (R>N) per year and per tunnel or per 1 km (semi-objective, quantitative)

– cost-effectiveness parameters; cost of safety measures in relation to their risk-reducing effects (semi-objective, quantitative)

Quantitative risk criteria can be adopted as absolute threshold values (a system is safe, if the relevant risk value of the system is lower than the defined threshold value) or in the way of relative comparison (e.g. comparison of different safety measures or comparison of a system to a “safe” reference system). Some quantitative criteria make it possible to also consider influences of risk perception (such as public effects of big disasters with many casualties) in the risk evaluation process (e.g. by reducing the risk limits for accidents with high consequences).

### 3.1.3 Data limitations

In contrast to traffic accidents on open roads, there is relatively little data on incidents in road tunnels and published statistics for a few countries only. Information on tunnel fires is notably still quite sparse.

When using incident statistics, it is important to consider any differences in the underlying safety levels. In practice, the incident rates vary between tunnels depending on factors such as country, location, geometry, traffic modes and flows, tunnel safety systems and management procedures. There may also be important historical trends in incident rates. Use of historical data without any correction for the trends and different circumstances may give misleading results which are inconsistent with observations of the frequency of vehicle fires in tunnels and on open routes.

Risk assessment methods may categorise fire scenarios according to heat release rates or the number and type(s) of vehicle(s) involved. In practice, it may be difficult to distinguish between some categories in statistical terms, which would suggest that fewer, broader categories should perhaps be used in such circumstances. The probability that a fire involving a heavy goods vehicle (HGV) will develop into a severe fire depends on the combustible nature and quantity of goods carried and whether the fire spreads to the load. Assumptions or estimates can be made for each of these aspects, but there is currently little supporting statistical data. The analysis of multiple vehicle accidents is particularly uncertain at present.

In terms of consequences, the reliable prediction of the numbers of fatalities and injuries is difficult because of the dominant and uncertain influence of human behaviour and the effects of hazardous conditions on people. Whilst modelling of evacuation and the effects of hazards on...
people can be carried out, the results will be constrained by the input and modelling assumptions. It may be possible to derive indicative estimates of the numbers of casualties from published tunnel incident reports, but this approach is complicated by the lack of information (for example, on the actual fire development). Without this, it may not be clear how to treat the incident.

### 3.2 Practical Methods

Within the framework of the activities of Working Group 2 an inquiry of the state of the art of the application of risk analysis in PIARC member states was carried out. The comprehensive results are published in a separate document, which is available at PIARC-website (www.collaborative.piarc.org/C3-3). This document contains a collection of questionnaires which provide information about

- Methodology
- Approach of risk evaluation
- Experience in practical application
- Suitability of method to meet specific requirements of the EU-Directive 2004/54/EC
- Recommendations

referring to the risk analysis methods which are practically applied by the respective countries. In this chapter 3.2 selected examples of practically applied risk analysis methods are documented. On the following pages a short description of the methodical approach, of the characteristics of its results and of the applied strategy of risk evaluation are presented. Special emphasis is put on information about range and limits of its application, to give advice to the reader, for which problems the respective method is suited or not. The description of the method refers to Figure 4 – overview of methodology components for risk assessment – in chapter 3.1, to better illustrate the elements the method consists of. Finally the suitability of the method to meet the specific requirements of EU-Directive 2004/54/EC is discussed.

Additionally, to each method described in chapter 3.2, a case study is presented in chapter 5 to provide a better understanding of the procedure, the achievable results and type and nature of addressable problems.

#### 3.2.1 Austrian Risk Model for Road Tunnels

**Methodical approach**

For the Austrian Risk Model for Road Tunnels a set of different methodical tools is used to analyse the whole system of safety relevant influencing factors; the method is a *system-based approach*, consisting of two main elements:

- quantitative frequency analysis
analytical approach (event tree analysis – logical trees) for analysing the sequence of events from an initial event (accident, breakdown) to a set of consequence scenarios

- statistical approach to quantify the initial events (accidents rates of tunnel accidents) and the distribution (relative frequencies) to the branches of the event tree

- quantitative consequence analysis

- statistical approach to quantify the consequences of mechanical effects of tunnel accidents

- combination of a distribution model (distribution of smoke in the tunnel) with a simulation model (simulation of self rescue of people in the tunnel) to quantify the consequences of fires

Results of risk analysis and strategy of risk evaluation

the risk model only covers the personal risks of tunnel users

- result of risk analysis is the expected value of the societal risk of the tunnel investigated

the respective shares of risk due to

- mechanical effects
- fires
- hazardous goods

are shown separately.

- risk assessment is done by relative comparison

  - of risk reducing effects of different safety measures
  - of the risk of the tunnel investigated to the risk of a reference tunnel

as reference case a tunnel of the same length, type and traffic characteristic fully complying with the minimum safety requirements as per EU-Directive is used. The divergences identified can be assessed in terms of risk. Alternative measures to offset the divergences can be evaluated; the safety assessment of safety measures can be completed by a cost-effectiveness analysis

Range and limits of application

The model can be used for a wide field of different applications, such as safety assessment of new or existing tunnels, support of decision making process for the selection of safety measures (new tunnels) or upgrading measures (existing tunnels), definition of priorities for upgrading measures, etc. The model was developed on the basis of the EU-Directive 2004/54/EC on minimum safety requirements for road tunnels and therefore also covers all fields of application
defined in the Directive (despite of hazardous goods transport). A lot of tunnel specific basic data was collected and evaluated during the development process, which has been integrated in the model or can be used as input data.

The model covers all types of road tunnels with longitudinal or cross ventilation, and all types of tunnel accidents with injuries (vehicle breakdowns with fire; vehicle accidents, vehicle accidents with fire)

The advantages of the model are

– the high flexibility of the individual methodical elements, so that it is applicable to almost every tunnel, ventilation or traffic configuration

– its capability to include the effects of almost every important safety relevant influencing factor in a quantitative way; one of its key elements is the modelling of the complex interaction of smoke propagation in the tunnel and the procedure of self rescue in the situation of a fire, which allows the investigation of all influences on the lapse of time within this process

– its simple, clearly understandable and easily comparable results

However the result of the model (expected value) do not include information about the distribution of different accident consequence classes (such as f-n-curves); therefore the model is not suited to specifically investigate accidents with very low probability and very high consequences. Hence, the model is not suitable for a more thorough investigation of the effects of accidents involving hazardous goods.

Suitability of method to meet specific requirements of EU-Directive 2004/54/EC

According to annex 1 of the EU-Directive 2004/54/EC in specific situations risk assessment is required for the parameters listed below. Referring to the respective chapters of annex 1 it is indicated below whether this method is suited to perform the investigations required.
| Chapter 1.1.3 | Assessment of influence of specific characteristic of relevant parameters | yes; in most cases | Chapter 2.6.2 | Permission of hazardous goods transport | no; for this purpose the PIARC/OECD model is used |
| Chapter 1.2.1 | Assessment of discrepancies to minimum safety requirements | yes | Chapter 2.9.3 | Decision on ventilation system | yes |
| Chapter 1.3.2 | Assessment of influence of number of heavy goods vehicles | yes | Chapter 3.4 | decision on location of rescue services | no |
| Chapter 2.2.3 | Assessment of influence of high gradient | Yes, but this requires statistical information on the influence of gradient on incident frequencies. | Chapter 3.7 | analyse risks due to transport of dangerous goods | no; for this purpose the PIARC/OECD model is used |
| Chapter 2.2.4 | Assessment of influence of narrow traffic lanes of heavy goods vehicles | Yes, but this requires statistical information on the influence of lane width on incident frequencies. | |

### 3.2.2 French Risk Analysis for Road Tunnels

**Methodical approach**

As part of the Safety Documentation, Specific Hazard Investigations are performed for every tunnel above 300m. Those studies represent risk analysis in conformity with the provisions of Article 13 of 2004-54-CE Directive.

A booklet, part of “Guide to Road Tunnel Safety Documentation” is dedicated to Specific Hazard Investigations (booklet 4), so as to provide methodological guidance for those studies.

The investigation (*scenario-based approach*) is conducted in accordance with the following plan:

- Chapter 1: Overview of the tunnel and its environment
- Chapter 2: Functional description of the tunnel
- Chapter 3: Identification of hazards and choice of scenarios
- Chapter 4: Examination of the scenarios
- Chapter 5: Summary.

To perform such studies, a set of different tools is used. In particular:

- A quantitative assessment of frequencies of trigger events is performed;
A semi-quantitative approach is used to rank trigger events, with help of a standardised Frequency x Consequence matrix:

<table>
<thead>
<tr>
<th></th>
<th>I Minor or None</th>
<th>II Significant</th>
<th>III Critical</th>
<th>IV Catastrophic</th>
<th>V Major Catastrophe</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Very frequent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Frequent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Occasional</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Rare</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Very rare</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Extremely rare</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A quantitative consequence analysis (spread model, simulation etc.) is performed by studying a set of representative scenarios, selected in the above mentioned matrix, and using standardised source terms for fires. That kind of study (i.e. to quantify the consequences of fires) generally considers a combination of a model to assess smoke and temperature conditions in the tunnel with a model to assess self rescue of people.

Results of risk analysis

The main results of the Specific Hazard Investigations are generally summarised as follows:

- Estimation of compliance with widely accepted practice of measures intended to reduce the probability of occurrence of accidents;
- For tunnels in operation not compliant with French 2000-63 technical instruction and/or 2004-54 European Directive, an assessment of the level of safety is performed aiming to evaluate of deviations from standards are acceptable or not regarding safety;
- The scope of measures intended to reduce both the occurrence and the consequences of accidents is listed;
- Assessment of adequacy of measures taken to reduce the consequences of equipment failures, and verification of absence of a common failure mode for equipment designed to ensure safety;
- Where applicable, proposals for the improvement of the provisions adopted are performed.

Those conclusions are stressed with regards to safety of road users, and their ability to rescue themselves with help of tunnel equipments and operation.
Range and limits of application

The method is used for a wide field of different tunnels, from tunnels in project to complex tunnels in operation, for which the level of safety after refurbishment needs to be assessed.

To summarise, the information taken from the specific hazard investigation makes it possible to:

• suggest, if needed, improvements to the reference condition (for new tunnels: tunnel at commissioning stage; for tunnels in operation: tunnel stage after refurbishment), or even, in exceptional cases, to question the decisions taken;

• have, in every case, the basic data the tunnel owner needs to develop operating instructions (including the minimum operating conditions) and, in collaboration with the emergency services, the required emergency response plans.

The advantages of this methodology, because standardised by guidelines (booklet 4), are:

• To allow both, a specific approach whatever the tunnel is, and standardisation of the way to assess frequencies of trigger events;

• To allow comparability of risk levels from one tunnel to another;

• Its capability – by applying a scenario based approach – to take account of the effects of almost every important safety relevant influencing factor in a quantitative way, by modelling of the complex interaction of smoke propagation in the tunnel and the procedure of self rescue in the situation of a fire.

However such studies are sometimes too costly in simpler situations (such as short and recent well monitored twin bore tunnels). In particular, engineers who perform such studies sometimes do not choose the right models or the adequate level of detail for this sort of investigation (simple 1D models or even qualitative approach for simpler cases, and complex 3D models for complicated situations).

Moreover, such a scenario based approach may not be the most efficient tool to investigate accidents involving hazardous materials that have potentially violent effects (explosives, LPG…).

Suitability of method to meet specific requirements of EU-Directive 2004/54/EC

According to annex 1 of the EU-Directive 2004/54/EC in specific situations risk assessment is required for the parameters listed below. Referring to the respective chapters of annex 1 it is indicated below whether this method is suited to perform the investigations required.
<table>
<thead>
<tr>
<th>Chapter 1.1.3</th>
<th>Assessment of influence of specific characteristic of relevant parameters</th>
<th>Yes, in comparative way, for some parameters</th>
<th>Chapter 2.6.2</th>
<th>Permission of hazardous goods transport</th>
<th>Not done using specific hazard investigation, but by applying DG QRA model (see chapter 3.2.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 1.2.1</td>
<td>Assessment of discrepancies to minimum safety requirements</td>
<td>Yes, especially for tunnels in operation that need to be refurbished</td>
<td>Chapter 2.9.3</td>
<td>Decision on ventilation system</td>
<td>Some sensitivity studies can be carried out if needed to provide information for decision making process</td>
</tr>
<tr>
<td>Chapter 1.3.2</td>
<td>Assessment of influence of number of heavy goods vehicles</td>
<td>Comparative studies can be carried out, but it is generally not investigated</td>
<td>Chapter 3.4</td>
<td>Decision on location of rescue services</td>
<td>Except for special cases (Fréjus, Mont-Blanc, Maurice Lemaire tunnels), generally not relevant because location of rescue services depend also on other infrastructures locations (buildings accessible to public, ...)</td>
</tr>
<tr>
<td>Chapter 2.2.3</td>
<td>Assessment of influence of high gradient</td>
<td>Comparative studies can be carried out, but never done yet</td>
<td>Chapter 3.7</td>
<td>Analyse risks due to transport of dangerous goods</td>
<td>Not done using specific hazard investigation, but by applying DG QRA model (see chapter 3.2.7)</td>
</tr>
<tr>
<td>Chapter 2.2.4</td>
<td>Assessment of influence of narrow traffic lanes of heavy goods vehicles</td>
<td>Comparative studies can be carried out, but never done yet</td>
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### 3.2.2 Dutch Scenario Analysis for Road Tunnels

**Methodical approach**

The *scenario analysis* is a deterministic method (*scenario based approach* – not a model) that can be used to identify possible weak spots in the whole tunnel system (technical and organisational measures). It aims at optimising the management of the processes occurring before, during and after an accident. The focus is on self-rescue and emergency response.

A limited number of scenarios is analysed in detail to assess the effectiveness of the technical and organisational measures to control and influence the possible developments of these scenarios.

Only traffic-related accidents are dealt with: breakdowns, collisions, fire, explosion, spill of dangerous goods.

The method consists of:

- A system description;
• A selection of relevant scenarios;
• An analysis of effects and consequences;
• An evaluation of the results and an optimisation of the design.

The frequencies of the scenarios only play a role in the selection of relevant scenarios.

The consequence analysis is done in a qualitative way: in time-steps an overview of the development of the accident and the status of the tunnel system is elaborated.

Also (calculated) quantitative information is added like the number of people in the tunnel, the fire load, the effect distances and the numbers of casualties. It is also possible to implement effect models.

Results of risk analysis and strategy of risk assessment

Before the beginning of the scenario analysis criteria on prevention, mitigation, self-rescue and emergency response are set. The results of the scenario analysis are:

• a description of a number of scenario developments in a qualitative and quantitative way;
• an evaluation against the criteria;
• conclusions;
• recommendations for improvement.

Suitability of method to meet specific requirements of EU-Directive 2004/54/EC

According to annex 1 of the EU-Directive 2004/54/EC in specific situations risk assessment is required for the parameters listed below. Referring to the respective chapters of annex 1 it is indicated below whether this method is suited to perform the investigations required.
3.2.5 Dutch TUNPRIM model

Methodical approach

The TunPrim model is a spreadsheet model (system based approach) for a quantitative risk analysis. The model is designed to calculate the internal risk in 2 bore tunnels with unidirectional traffic and longitudinal ventilation.

Incidents that are taken into account are: collisions, fire, explosion and leakage of aggressive and toxic materials.

For the frequency calculation event tree analysis is used.

Consequences for each branch of the event tree are calculated in terms of number of fatalities.

Three categories of fatalities are calculated: ‘direct’ victims (due to ‘normal’ traffic accidents), victims due to entrapment in a vehicle fire, and victims due to the effects of fires, explosions and/or exposure to toxic substances.

Results of risk analysis and strategy of risk assessment

The risk is presented as:

- *Expected Value*, this is the average number of fatalities per year. The individual risk (the risk for persons per km per year) is derived from the Expected Value, the length of the tunnel, the annual number of vehicles and the average occupation in a vehicle.
• **Societal Risk** (F/N-curves, a graph of the frequency of the occurrence of accidents with N or more deaths).

In the Netherlands risk acceptance criteria have been defined for tunnel users: a personal risk of $1,0 \times 10^{-7}$ per km and a societal risk of $1,0 \times 10^{-1}/(N^*N)$ per km per year. These values do not have a legal status yet.

The model is used to compare alternatives and the influence of (additional) measures.

**Suitability of method to meet specific requirements of EU-Directive 2004/54/EC**

According to annex 1 of the EU-Directive 2004/54/EC in specific situations risk assessment is required for the parameters listed below. Referring to the respective chapters of annex 1 it is indicated below whether this method is suited to perform the investigations required.

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<thead>
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<th>Chapter 1.1.3</th>
<th>Yes</th>
<th>Chapter 2.6.2</th>
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<tr>
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<td>Assessment of influence of number of heavy goods vehicles</td>
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<tr>
<th>Chapter 2.2.3</th>
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<td>Assessment of influence of high gradient</td>
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<tr>
<th>Chapter 2.2.4</th>
<th>No</th>
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<tr>
<td>Assessment of influence of narrow traffic lanes of heavy goods vehicles</td>
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3.2.6 Italian Risk Analysis for Road Tunnels

The Italian approach to safety of road tunnels fits in the framework of the European Directive 2004/54/CE and in particular requires risk analysis to be developed for those tunnels where the minimal safety conditions (stated by the Directive) are not completely satisfied or for those ones which are characterized by special conditions (in terms of length, traffic volume, number of tubes etc.). This is also the range in which an outgoing decree of the Ministry of Transportation and Infrastructures is going to limit the requirement of developing risk analysis.

Methodical approach

The Italian risk analysis method is essentially based on quantitative probability estimates and quantitative consequence analysis (scenario analysis). According to a kind of event tree analysis scheme (logical trees), a suitable set of initial triggering events (associated in particular to the occurrence of fire in tunnels) together with a sequence of sub-events associated to the behaviour of the sub-system, the tunnel is endowed with, are assumed to characterize the complete group of mutually independent consequence events which describe the event space.

Probability estimate for the considered triggering events is typically based on a statistical approach and refers in particular to fire accident rates in tunnels; on the other hand probability estimate of the events which characterize the behaviour of the tunnel sub-systems derive from the reliability performance of the devices with which the tunnel is equipped. Apparently the probabilities associated to the different branches of the event tree depend on both these two aspects together with the randomness characterization of the people escaping inside the tunnel.

Consequence analysis is developed in order to determine, from the physical point of view, what are the spatial and time distributions of the physical parameters which mainly affect the environment where the self rescue of the people affected by the accident occurs. Therefore the focus is in particular on the temperature field, the smoke density, the visibility (in terms of optical density) and the concentration of toxic substances; all these parameters tend to affect in different ways people’s escape along different branches of the event tree, according to the behaviour of the sub-systems.

Consequences are generally measured in terms of fatalities, however there is no a-priori constraint to adapt alternative/complementary utility indicators involving for instance also injuries and damage to the infrastructure.

Results of risk analysis

The Italian approach to risk assessment implies that two different risk indices can be used. The first one is based on the expected level of fatalities per year over the considered tunnel; it is considered for a kind of comparison analysis when dealing with tunnels which do not satisfy the complete set of minimal requirements, as stated by the European Directive 2004/54/CE, but are
endowed with additional alternative/complementary equipments. If the value of this expected risk index is smaller than or equal to the corresponding one associated to the case of the standard tunnel (the same tunnel endowed with the complete set of minimal requirements) then no additional investigation is necessary and the alternative design can be accepted, assuming that the technical capability of the considered sub-systems do guarantee the envisaged performance. In the opposite case and in general when the considered tunnel is characterized by special conditions then a complete risk analysis procedure is mandatory to be developed also to guarantee that the envisaged performance of the sub-systems can really be achieved. In this case the acceptability of the (alternative) design choice has to be verified considering the societal risk (or cumulative risk) associated to the tunnel, this risk index is defined by the complementary cumulative distribution associated to number of fatalities (per year) associated to the considered tunnel.

Placing this function in the F-N plane and considering it with respect to the level of tolerable risk and the level of acceptable risk shows, whether the adopted design methodology can be accepted or not.

**Range and limits of application**

The risk model can be adopted for risk assessment of existing tunnels and new tunnels, in particular for selecting the proper additional complementary equipments the tunnel has to be endowed with, or the alternative safety measures to be adapted when there is no chance of implementing all the minimal requirements typical of the considered tunnel.

No special limitations for applying the envisaged method to the whole set of possible tunnels are stated, however some additional requirements should be taken into account when considering the management and transportation of dangerous goods.
Suitability of method to meet specific requirements of EU-Directive 2004/54/EC

According to annex 1 of the EU-Directive 2004/54/EC in specific situations risk assessment is required for the parameters listed below. Referring to the respective chapters of annex 1 it is indicated below whether this method is suited to perform the investigations required.

<table>
<thead>
<tr>
<th>Chapter 1.1.3</th>
<th>Chapter 2.6.2</th>
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<tbody>
<tr>
<td>Assessment of influence of specific characteristic of relevant parameters</td>
<td>Permission of hazardous goods transport</td>
</tr>
<tr>
<td>Chapter 1.2.1</td>
<td>Chapter 2.9.3</td>
</tr>
<tr>
<td>Assessment of discrepancies to minimum safety requirements</td>
<td>Decision on ventilation system</td>
</tr>
<tr>
<td>Chapter 1.3.2</td>
<td>Chapter 3.4</td>
</tr>
<tr>
<td>Assessment of influence of number of heavy goods vehicles</td>
<td>decision on location of rescue services</td>
</tr>
<tr>
<td>Chapter 2.2.3</td>
<td>Chapter 3.7</td>
</tr>
<tr>
<td>Assessment of influence of high gradient</td>
<td>analyse risks due to transport of dangerous goods</td>
</tr>
<tr>
<td>Chapter 2.2.4</td>
<td></td>
</tr>
<tr>
<td>Assessment of influence of narrow traffic lanes of heavy goods vehicles</td>
<td></td>
</tr>
</tbody>
</table>

3.2.6 UK Risk Analysis for Road Tunnels

The UK Highways Agency is funding a research project ‘Risk Analysis Methods for Road Tunnels’. The purpose of the study is to determine the most appropriate means of analysing and evaluating risk in relation to safety in road tunnels and to develop risk analysis tools for the use of practitioners, leading to improved and consistent decisions to be made on the grounds of safety in the design and operation of road tunnels. The tools will form the basis of a national approach. It is anticipated that the project will be completed during 2006.

Currently, a range of risk analysis methods are used:

- Qualitative analysis of risks affecting design and operation of road tunnels, for example using a method defined in the UK road tunnel standard, BD 78/99;
- Deterministic analysis of selected scenarios, for example using CFD modelling;
Probabilistic risk analysis, including both project-specific methods used to support decision making on the adoption and definition of certain safety facilities, and the DG QRA model from OECD/PIARC for dangerous goods transport through road tunnels.

In the case study in chapter 5.5 the application of different methods - to investigate various issues – for one specific tunnel is demonstrated

Suitability of method to meet specific requirements of EU-Directive 2004/54/EC

According to annex 1 of the EU-Directive 2004/54/EC in specific situations risk assessment is required for the parameters listed below. Referring to the respective chapters of annex 1 it is indicated below whether this method is suited to perform the investigations required.

<table>
<thead>
<tr>
<th>Chapter 1.1.3</th>
<th>Assessment of influence of specific characteristic of relevant parameters</th>
<th>Parametric studies can be carried out.</th>
<th>Chapter 2.6.2</th>
<th>Permission of hazardous goods transport</th>
<th>The OECD/PIARC QRA model has been used for a number of studies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 1.2.1</td>
<td>Assessment of discrepancies to minimum safety requirements</td>
<td>Comparative studies can be carried out.</td>
<td>Chapter 2.9.3</td>
<td>Decision on ventilation system</td>
<td>A risk-based framework for ventilation design is available.</td>
</tr>
<tr>
<td>Chapter 1.3.2</td>
<td>Assessment of influence of number of heavy goods vehicles</td>
<td>yes</td>
<td>Chapter 3.4</td>
<td>decision on location of rescue services</td>
<td>no</td>
</tr>
<tr>
<td>Chapter 2.2.3</td>
<td>Assessment of influence of high gradient</td>
<td>This requires statistical information on the influence of gradient on incident frequencies.</td>
<td>Chapter 3.7</td>
<td>analyse risks due to transport of dangerous goods</td>
<td>The OECD/PIARC QRA model has been used for a number of studies.</td>
</tr>
<tr>
<td>Chapter 2.2.4</td>
<td>Assessment of influence of narrow traffic lanes of heavy goods vehicles</td>
<td>This requires statistical information on the influence of lane width on incident frequencies.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2.7 DG QRA Model from OECD/PIARC – application in France

Methodical approach

As part of the Safety Documentation, Risk Analysis for Transport of Dangerous Goods are performed for every tunnel above 300m. For that purpose, the DG QRA model developed by OECD/PIARC is used.

In a first step, an expected risk value for the tunnel itself is calculated. It corresponds to the yearly expected number of victims due to dangerous goods transported through the considered route or tunnel. In case of a series of tunnels a cumulated expected value is calculated. For that purpose the following data is needed:

- DG traffic volume and composition,
- Global traffic volume, composition (cars, HGV, coaches/busses), and daily/seasonal variations,
- Accident rate in the tunnel,
- Tunnel characteristics (length, longitudinal and cross sectional geometry, ventilation, drainage system, emergency exits, …)

The data used refers to the situation 10 years after a tunnel is put into operation (for tunnels in project or tunnels at commissioning stage), or 10 years after the date when the QRA study is performed (for in-service tunnels).

If the expected value calculated for the tunnel is above a certain limit, then DG QRA model is used to compare alternative routes (tunnel route and alternatives). Up to 3 alternatives can be selected. The QRA study is then performed in the following way:

- Data collection for the alternative routes, with an homogeneous level of detail for every compared routes,
- Calculation of societal risk for every routes to compare (F/N curves, expected values),
- Comparison of curves (for the whole traffic, for some groups of hazardous goods, or with considering transport limitation measures at predetermined periods of time),
- Sensitivity study on the main parameters (generally: population data, DG traffic, global traffic, accident rates).

The DG QRA model allows a quantitative approach, by means of:

- quantitative frequency analysis
  - The DG QRA model includes results of an analysis of the sequence of events from an initial event (accident, breakdown) to a set of consequence scenarios, translated into...
conditional probabilities to get scenarios given an accident happened. A table has been established and included in the model that includes quantitative figures for each scenarios, which distinguishes between different boundary conditions (tunnel/open air routes, urban/rural areas),

- Accidents rates on tunnel/open air routes are described by the user of the model, as well as their variations all along the routes, on the basis of national wide statistics (default values, generally used for tunnels in project), or local statistics (observation of accidents for the investigation of in-service roads/tunnels)

- quantitative consequence analysis

  - A 2D and a simpler 1D software tool, based on predetermined calculations of physical consequences in the open (with considering a set of meteorological conditions), have been implemented in the DG QRA model so as to assess consequences for road users and local population in the vicinity of the roads, of a set of scenarios representative to the observed DG traffic.

  - A 1D excel based software tool (pre-conditioner) has been implemented to calculate physical and physiological consequences of scenarios

The way all the software tools and tables are organised in the model is broadly the following:

The combination of quantitative frequency and consequence analyses/calculations allows the calculation of F/N curves.
The DG QRA model is based upon the following set of 13 representative scenarios:

<table>
<thead>
<tr>
<th>Scenario Nr:</th>
<th>Description</th>
<th>Capacity of tank</th>
<th>Size of breach (mm)</th>
<th>Mass flow rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HGV fire 20 MW</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>HGV fire 100 MW</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>BLEVE of LPG in cylinder</td>
<td>50 kg</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Motor spirit pool fire</td>
<td>28 tonnes</td>
<td>100</td>
<td>20.6</td>
</tr>
<tr>
<td>5</td>
<td>VCE of motor spirit</td>
<td>28 tonnes</td>
<td>100</td>
<td>20.6</td>
</tr>
<tr>
<td>6</td>
<td>Chlorine release</td>
<td>20 tonnes</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>7</td>
<td>BLEVE of LPG in bulk</td>
<td>18 tonnes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>VCE of LPG in bulk</td>
<td>18 tonnes</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>9</td>
<td>Torch fire of LPG in bulk</td>
<td>18 tonnes</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>10</td>
<td>Ammonia release</td>
<td>20 tonnes</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>11</td>
<td>Acrolein in bulk release</td>
<td>25 tonnes</td>
<td>100</td>
<td>24.8</td>
</tr>
<tr>
<td>12</td>
<td>Acrolein in cylinder release</td>
<td>100 litres</td>
<td>4</td>
<td>0.02</td>
</tr>
<tr>
<td>13</td>
<td>BLEVE of liquefied refrigerated air</td>
<td>20 tonnes</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

These scenarios do represent the main unexpected effects that can be encountered: large explosions with or without thermal effects, major toxic effects from accidental releases of gases or volatile liquids, large fires.

Thus, from an observed DG traffic, most of the goods can be represented by this set of scenarios.
Results of risk analysis and strategy of risk evaluation

The Results produced by the DG QRA model are generally presented in the form of F/N curves:

![Image of F/N curves]

in this figure F/N curves and the resulting expected values for the 2 compared routes are presented (one including a tunnel, the other being the considered alternative).
For the purpose of risk evaluation, the following flowchart is considered:

IR is the intrinsic risk value (expected value) for the tunnel. This value is obtained when applying the DG QRA model for the tunnel only, as described above in the methodical approach section (first step of risk analysis). If IR > 0.001 for a given tunnel, then a QRA study is carried out to compare tunnel and alternative routes. If IR < 0.001, then risk due to dangerous goods transport is considered as not being an issue, and decision regarding authorisation or not of dangerous goods transport can be decided on the basis of other criteria than derived from QRA application.

When a complete QRA study is needed (second step of risk analysis), the DG QRA model is used to compare the risk level due to carried DG on the tunnel route with the risk level due to carried DG on alternative routes.

The result of the risk analysis for dangerous goods transport is a proposal for the decision of the administrative authority on authorising totally, partially or forbidding DG traffic in the investigated tunnel.
Range and limits of application

The model is well suited to take decisions regarding DG traffic authorisation or not in a tunnel. The model is not suitable for a general risk analysis for road tunnels. It is generally difficult to communicate with local authorities using that sort of study.

Suitability of method to meet specific requirements of EU-Directive 2004/54/EC

According to annex 1 of the EU-Directive 2004/54/EC in specific situations risk assessment is required for the parameters listed below. Referring to the respective chapters of annex 1 it is indicated below whether this method is suited to perform the investigations required.

| Chapter 1.1.3 | Assessment of influence of specific characteristic of relevant parameters | for DG traffic only | Chapter 2.6.2 | Permission of hazardous goods transport | yes |
| Chapter 1.2.1 | Assessment of discrepancies to minimum safety requirements | for DG traffic only | Chapter 2.9.3 | Decision on ventilation system | no; because only DG traffic investigated. |
| Chapter 1.3.2 | Assessment of influence of number of heavy goods vehicles | yes | Chapter 3.4 | decision on location of rescue services | no |
| Chapter 2.2.3 | Assessment of influence of high gradient | for DG traffic only | Chapter 3.7 | analyse risks due to transport of dangerous goods | yes |
| Chapter 2.2.4 | Assessment of influence of narrow traffic lanes of heavy goods vehicles | for DG traffic only; requires statistical information on lane width on incident frequencies | | | |
4. State of the Art of Risk Analysis in selected PIARC Member States

In April 2004 the Directive 2004/54 EC of the European Parliament and of the Council on minimum safety requirements for tunnels in the Trans-European road network [15] was issued. According to Article 13 of the Directive risk analyses are to be carried out in certain cases taking into account all design factors and traffic conditions that affect safety. Furthermore member states shall ensure that, at national level, a detailed and well-defined methodology, corresponding to the best available practices, is applied.

Therefore it was decide to prepare a documentation of the state of the art of risk analysis in PIARC member states as one of the elements of the present report on risk analysis. For that purpose a questionnaire was elaborated and sent to all WG 2 members. Based upon the work of Safe T, Task 5.1 [16] the existing practice and envisaged further developments in application of risk analysis in many European PIARC member states as well as in Canada, USA and Japan were investigated. The results are presented in this chapter.

The following countries contributed to the present chapter (in alphabetic order):

– Austria    – Japan
– Canada     – The Netherlands
– Czech Republic  – Norway
– Denmark    – Portugal
– France     – Sweden
– Germany    – Switzerland
– Great Britain – USA
– Italy

The present chapter is intended to give a short summary about the use of risk analysis methods in these countries. Details about the individual methods, the concept of risk evaluation, the experience in practical application and the suitability of the methods to meet specific requirements of the EU-Directive are documented in the questionnaires which are published in a separate document at PIARC webpage.
4.1 Countries with several years of experience in application of risk analysis

4.1.1 Canada (QUEBEC)
In Quebec a deterministic, qualitative method of risk analyses is used for the investigation of elements of the road network in general. The method covers a wide range of different types of risks. For tunnels this method is specified concentrating on other threats such as fire, explosions and terrorism. The main objective is to assess the internal and external threat to critical elements of infrastructure resulting in a ranking.

4.1.2 France
As a consequence of the Mount Blanc Tunnel fire, a lot of research work on tunnel safety was carried out in France. As one result of this work guidelines on safety documentation were published in 2003. In booklet 4 the methodology and procedure for a “Specific Hazard Investigation” is presented.

This “Specific Hazard Investigation” is a scenario based, qualitative analysis (not a model) which can be flexibly adapted to specific situations and different levels of investigation. This method is also open to use quantitative elements such as smoke movement modelling or user behaviour modelling. The guideline standardizes key input data without regulating the method to be applied.

For the investigation of hazards due to the transport of hazardous goods in France the DG QRA model from OECD/PIARC is used.

4.1.3 Great Britain
In the UK, a flexible approach to tunnel safety design has been encouraged by the Highways Agency, through its standard BD 78/99 ‘Design of road tunnels’, in which safety measures are tailored according to the risks and circumstances.

A range of methods are used:

a) Qualitative analysis of risks affecting design and operation of road tunnels, e.g. using the RPN (Risk Priority Number) method defined in the standard BD 78/99.

b) Deterministic analysis of selected scenarios, e.g. using CFD modelling.

c) Probabilistic risk analyses, defined on an ad-hoc basis for different projects.
4.1.4 The Netherlands

The "Dutch scenario analysis for road tunnels" is a deterministic, scenario based risk analysis aiming to optimise the management of the process occurring before, during and after an accident. The method can be used flexibly and it is also possible to implement quantitative elements such as different kinds of effect models.

Another method used in the Netherlands is a QRA-model called “TunPrim”. TunPrim is an event tree analysis covering traffic accidents, fire explosions and leakage of aggressive and toxic material.

4.1.5 Norway

In Norway TUSI – a deterministic risk model – is used to calculate the probabilities of fire, accidents and other incidents in tunnels longer than 500 m.

The model is easy to use and delivers very good and verified results for accident frequencies for individual tunnel sections. However this method does not contain any form of consequence assessment. In single cases more comprehensive risk analyses are performed.

There are no risk acceptability criteria – risk evaluation is done by subjective judgement of the responsible tunnel management.

4.1.6 Sweden

In Sweden a deterministic risk analysis is performed. The method is mainly qualitative, but it is also possible to include quantitative elements, such as consequence models.

4.1.7 USA

In the USA deterministic and probabilistic methods are used, mainly for the investigation of fire scenarios.

In USA the assessment of road tunnels safety is mainly based on past experience. There is no national model. The risk analysis performed is aimed to optimise prevention of life and structure damage, before, during and after an accident.
4.2 Countries in the stage of developing and implementing new methodologies for risk analysis

4.2.1 Austria

In Austria the assessment of road tunnels safety in the past was based on experience and prescriptive guidelines. In the course of updating the Austrian design code for tunnel ventilation, it was decided to develop a methodology for an integrated quantitative risk analysis. Initially the main objective was to establish a risk-based decision tool for the specification of important safety requirements of road tunnels (e.g. ventilation system). In April 2004 the EU-Directive on road tunnel safety was issued. Article 13 of this directive obliges every member state to develop a method for a risk analysis on a national level. The requirements of the EU-Directive therefore where implemented in the design process of the new method. The method is now completed and has been successfully applied to several tunnels of the Austrian highway network.

The concept of risk assessment implemented in Austria is a comparative one, based upon the minimum safety requirements as defined in the EU-Directive.

For the investigation of issues of hazardous goods transport the DG-QRA model from OECD/PIARC is intended to use.

4.2.2 Czech Republic

In the framework of the project “Risk Analysis and Risk Management in Road Tunnels” (2001-2003) a quantitative methodology was developed and approved for Czech Republic. A first commercial model is being developed.

For the investigation of accidents with hazardous goods the DG-QRA model from OECD/PIARC is being implemented.

4.2.3 Denmark

There are only few road tunnels in Denmark and at the moment there is no decision which methodology of risk analysis is to be used at a national level with respect to article 13 of the EU-Directive. The current practice is, that risk analysis tools are adopted, but in each case the tunnel manager decides together with a consultant, which method is used.

4.2.4 Germany

In Germany the assessment of road tunnels regarding safety aspects is in most cases based on the application of mainly prescriptive guidelines (RABT), though the guidelines allow a risk based approach for certain cases.
In the past risk analyses have been carried out for new road tunnels in Germany however these analyses were not carried out on the basis of a unified approach which means that not in every case the full set of parameters mentioned in the EC-directive has been considered. For investigations regarding the transport of dangerous goods methods according the DG-QRA model from OECD/PIARC have been used.

Therefore a quantitative risk assessment model is currently being developed. The model will be based on a probabilistic risk analysis. The details of the method are not yet defined.

4.2.5 Italy

Until now no risk analysis has formally been required by the Italian authorities, only academic studies have been carried out. However the ANAS company which is the owner of the whole Italian road network is preparing new guidelines for the safety design of road tunnel, in accordance with the EU-Directive.

Therefore in Italy a research plan has been currently established to develop a complex, integrated quantitative methodology of risk analysis with respect to the requirements of the EU-Directive. The methodology shall implement all established elements of quantitative risk analysis, such as event tree analysis, smoke propagation model, people’s behaviour model etc. and shall cover all relevant types of tunnel accidents and their effects (including hazardous goods). The model shall also include the reaction of safety-relevant sub-systems, taking their reliability into account.

4.2.6 Portugal

There are only few road tunnels in Portugal and until now no decision has been made by the national authority which methodology of risk analysis is to be used at a national level with respect to article 13 of the EU-Directive.

The current practice is, that – if risk analysis tools are applied – the tunnel owner decides together with his consulter, which method is used. However, the national authority intends to implement risk analysis procedures as soon as possible.

4.2.7 Switzerland

In general Switzerland aspires to fulfil the requirements of the EU-Directive. Therefore a risk based safety evaluation of road tunnels according to article 13 of the EU-Directive shall be implemented.
Switzerland disposes of specific methodologies and experience in the application of quantitative risk analysis and evaluation, e.g. defined in the national regulations for the prevention of accidents with hazardous goods (so called “Störfallverordnung”). However, the “Störfallverordnung” is limited to the evaluation of transport of hazardous goods on defined road sections (including tunnels), focussing on effects on inhabitants and environment along these road sections. Therefore the method cannot easily be adapted to evaluate the risk of road tunnel users. A new construction guideline requires risk analysis for specific aspects without defining a method. At the moment no specific methodologies for risk analysis for road tunnels are developed.

4.3 Countries, which do not apply Risk Analysis

4.3.1 Japan

At present stage there is no risk analysis performed and there are no plans to implement risk analysis procedures in Japan.
5. Case Studies

5.1 Austrian Risk Model for Road Tunnels

5.1.1 Definition of the problem

An existing tunnel fulfils the requirements of the EU-Directive to a great extent. Only the number of heavy goods vehicles over 3,5 tonnes exceeds the reference value of the EU-Directive; according to Annex I, article 1.3.2 the respective additional risk has to be assessed. The additional risk shall be compensated. Therefore two possibilities of upgrading of the existing tunnel by additional safety measures shall be investigated by calculating their effects on risk.

5.1.2 Definition of the system

The following data describing the tunnel and its characteristics are also an import part of the input data of the risk model.

- Tunnel system: single tube tunnel
- Tunnel cross section: 46 m² (standard cross section for bidirectional tunnels in Austria)
- Tunnel length: 5.5 km
- Emergency exits: every 500m (to an already existing parallel tunnel remaining from the construction phase)
- Traffic (annual average daily traffic): 9,500 – bidirectional traffic
- Heavy goods vehicles: 25% (Reference value as per EU-Directive: 15%)
- Hazardous goods vehicles: 1,5% of heavy goods vehicles
- Buses: 1,25%
- Ventilation: Cross ventilation with smoke extraction openings with dampers every 100 m with a capacity of 120 m³ (in accordance with Austrian design guidelines)
- Automatic fire detection system: existing
- Information system for car drivers: existing
- Additional safety measures to be investigated
  - cross passages every 250 m to the already existing parallel tunnel
  - construction of a second tunnel tube
5.1.3 Probability Analysis

The probability analysis is done by an event tree model (Figure A)

![Event Tree Model](image)

**Figure A**: Principle of the event tree model

In the event tree analysis three different accident types are distinguished (see Table A)

<table>
<thead>
<tr>
<th>Accident Type</th>
<th>Bidirectional Tunnel</th>
<th>Unidirectional Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>single car crash</td>
<td>17 %</td>
<td>40 %</td>
</tr>
<tr>
<td>front-end collision</td>
<td>50 %</td>
<td>59 %</td>
</tr>
<tr>
<td>head-on collision</td>
<td>33 %</td>
<td>1 %</td>
</tr>
</tbody>
</table>

**Table A** relative share of accident types in unidirectional and bidirectional road tunnels in Austria

An important element of the input data for the probability analysis are tunnel specific accident rates; based upon the results of a comprehensive study of important tunnel specific characteristics of accident rates the following influence factors are considered:

- traffic volume
- unidirectional or bidirectional traffic
- tunnel length

Result of the event tree model are event probabilities for defined consequence scenarios. The event tree covers the following consequence scenarios:
breakdown | accidents | accidents with fire (as consequence) \\
--- | --- | --- \\
– car fire | mechanical effects – car accident | – car fire \\
– lorry fire | mechanical effects – accident including a lorry | – lorry fire \\
– lorry fire – involving flammable liquids 1) | mechanical effects – accident including a bus | – lorry fire – involving flammable liquids 1) \\
– bus fire | mechanical effects with release of hazardous materials 1) | – bus fire \\

1) general approach only

Table B Consequence scenarios considered in the event tree analysis

5.1.4 Consequence Analysis

Car accidents with mechanical effects

The accidents consequence data are taken from an evaluation of about 450 tunnel accidents in 81 Austrian road tunnels in the period 1999-2003 (61 unidirectional and 20 bidirectional tunnel mainly on Austrian motorways)

Fires

The consequence modelling of fire accidents is done by a combination of a one dimensional fire & ventilation model with an evacuation simulation model. As result of the consequence analysis, for each fire scenario defined by the event tree an average number of fatalities is calculated

Ventilation Model

In the ventilation model, two different fire scenarios (5MW, 30MW) und two different ventilation regimes can be selected

– longitudinal ventilation

– transverse ventilation, with impact on longitudinal air velocity
**Transverse ventilation, with impact on longitudinal velocity**

![Diagram of transverse ventilation](image)

**Longitudinal ventilation**

![Diagram of longitudinal ventilation](image)

**Figure B** Principle of ventilation model

The input parameters used in the analysis for the ventilation model are defined in accordance with the Austrian guidelines, some values also being based upon practical experience. They are valid for standard situations. However, the model makes it possible to investigate also non-standard ventilation systems and non-standard situations, but this requires higher expenses.

**Evacuation simulation model**

In the evacuation simulation model, the location of the accident in the tunnel, the location of emergency exits, the constellation of the vehicles on both sides of the accident, the propagation of smoke, the reaction of the people and their evacuation in the tunnel towards an emergency exit (a tunnel portal) are taken into account. This approach makes it possible to investigate all influences, which may effect the lapse of time concerning the interaction of propagation of smoke and self rescue, such as

- fire alarm / start of ventilation
- reaction of people
- walking velocity with/without smoke
- walking distances
- congestion effects etc.
For normal conditions standard parameters are defined in the evacuation simulation model. However all kinds of safety measures, that influence the sequence of self rescue, can be investigated by a detailed investigation. This, however, requires higher expenses.

5.1.4 Results of Risk Estimation

As reference value the expected value of the societal risk is used (fatalities/year); a distinction is made between risk due to car accidents with mechanical effects only, due to fires and due to hazardous goods accidents.

For the tunnel investigated the following results are obtained
share in risk

<table>
<thead>
<tr>
<th>share in risk</th>
<th>societal risk – expected value (fatalities/year)</th>
<th>mechanical effects</th>
<th>fire</th>
<th>hazardous goods</th>
</tr>
</thead>
<tbody>
<tr>
<td>existing tunnel (25% heavy goods vehicles)</td>
<td>0,257</td>
<td>86 %</td>
<td>14 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>existing tunnel (15% heavy goods vehicles)</td>
<td>0,236</td>
<td>85 %</td>
<td>15 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>cross passages every 250 m</td>
<td>0,242</td>
<td>91 %</td>
<td>9 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>second tunnel tube</td>
<td>0,0802</td>
<td>98 %</td>
<td>&lt;&lt; 1 %</td>
<td>2 %</td>
</tr>
</tbody>
</table>

**Table C**: Results of case study

---

**5.1.6 Results of Risk Evaluation**

Risk evaluation is done by relative comparison, mainly by comparing the tunnel as it is to the situation as it should be, taking the requirements of the EU-Directive into account. In our example the risk evaluation could be done as follows:

- The high portion (25%) of heavy goods vehicles causes an increase of risk of about 8,9% compared to the reference value according to the EU-Directive

The additional safety measures envisaged contribute to risk reduction as follows
– cross passages every 250 m can reduce risk by about 6%; this is almost the same order of magnitude as the additional risk, caused by the high portion of heavy goods vehicles; this measure considerably reduces fire risk but does not influence the risk portion due to accidents with mechanical effects

– a second tunnel tube considerably reduces the risk level of the tunnel to about one third of the initial value

From the safety point of view the measure “cross passages every 250 m” is an adequate measure for the compensation of the higher risk due to the high portion of heavy goods vehicles. This additional safety measure not only reduces the expected risk value by 6%, but also reduces the share of fire risk in the total risk value. For cost-benefit reasons this measure is recommended but it should be complemented by other measures which are able to reduce the risk due to mechanical effects as well.

Although very effective in terms of risk reduction, for cost-benefit reasons a second tunnel tube can only be justified, when the traffic volume is expected to increase considerably (up to 20,000 during the next 15 year – with reference to the EU-Directive, Annex I, article 2.1.2).
5.2 French Risk Analysis for Road Tunnels – Specific Hazard Investigation

Contribution was not delivered in time
5.3 Dutch Scenario Analysis for Road Tunnels

5.3.1 Scenario analysis: expansion of Coen tunnel capacity

This memorandum sets out the results of a scenario analysis that was performed in connection with the expansion of the capacity of the Coen tunnel.

5.3.2 Objective

The aim of the scenario analysis is:

- To test the design of the tunnel system against established safety objectives and requirements, whereby self-rescue and the emergency services deserve careful attention;
- Following on from this: to identify the opportunities for optimisation, which can be included in the further development of the design and structure of the management organization.

5.3.3 Step-by-step plan

In order to ensure verifiability, the objectives and requirements are linked to the assessment criteria.

Traffic handling (prevention):

Objective: Emergency procedures and measures will need to be in place to direct traffic flows around the tunnel in the event of (serious) incidents

Assessment criteria: Traffic flow will be sufficiently restricted.

Traffic jams in the tunnel will be prevented as much as possible. If traffic jams do occur in the tunnel, they will be cleared as quickly as possible. A diversion route must be set up if the tunnel has to be closed.

Dealing with incidents (preparation):

Objective: The combination of measures and provisions by the management organization and emergency services must be such that the consequences of any relevant types of incidents can be limited as much as reasonably possible.

Assessment criteria: Injury must be limited.

Damage to tunnel must be limited.

Duration of tunnel (tube) closure must be limited.
Self-rescue (correction):

Objective: The conditions of the Buildings Decree must be met.

Assessment criteria: The capacity must be adequate to allow unobstructed escape to a safe area.

Emergency assistance (repression):

Objective: The location of the incident is sufficiently accessible for the emergency services from the tunnel entrances.

Assessment criteria: The period of time between the moment the emergency services arrive at the tunnel access point and the moment they reach the location of the incident may not exceed 10 minutes.

Emergency services must have access to all tunnel tubes from each tunnel opening, in so far as space allows.

5.3.4 Description of tunnel system

In order to implement the scenario analysis, a reference description of the tunnel system will be used as the basis, a brief summary of which follows below:

- 2 immersed tunnels, enclosed for about 650 metres, a total of 4 traffic tubes; traffic flow in one direction per tube.
- Traffic intensity: 260,000 movements per 24 hours, goods transport: 10%; tunnel category I (no flammable/toxic gases in bulk permitted).
- Civil engineering safety measures present: central tunnel tube, safety barriers, water discharge systems, escape routes.
- Safety systems present: ventilation, lighting, signage, aid stations, escape route signage, emergency power supply.
- Safety organization present: contingency plan, emergency button, evacuation button.

A quantitative risk analysis has shown that according to this system description the expansion of capacity of the Coen tunnel complies with the requirements relating to personal risk and group risk of tunnel users. According to the guideline scenario analysis, this is a condition since the scenario analysis must be carried out based on a tunnel design demonstrating that it complies with these requirements.
5.3.5 Selection of scenarios to be analysed

In a scenario analysis, a limited number of relevant scenarios are considered. These scenarios must be representative of the tunnel system to be considered. In order to meet this condition, the following steps are followed to arrive at a choice of scenarios to be analysed:

1. Determine starting points for the choice.
2. Draw up a list of scenarios that may potentially be considered, taking account of the characteristics and specific circumstances of the tunnel.
3. Draw up a short description per scenario: the undesirable incident with the nature and extent of the consequences.
4. Assess scenarios against system description: are all system variables taken into consideration?
5. Assess scenarios against generic selection criteria:
   - Realistic and likely: is there a reasonable chance that the scenarios will occur?
   - Functional and effective: can safety objectives and measures be assessed with the scenarios?
   - Representative and balanced: do the scenarios to be chosen represent the complete range of conceivable scenarios; is the selection broad and well-balanced?
6. Definitive choice of scenarios to be analysed.

Ultimately the following scenarios were selected:

- Breakdown in west tube of 2nd Coen tunnel
- Collision in traffic jam (evening rush hour) in east tube of 2nd Coen tunnel
- Multiple collision in west tube of existing Coen tunnel
- Fire in cargo on goods vehicle (50MW) in morning rush hour in west tube of 2nd Coen tunnel
- Fire from petrol spillage in east tube of 2nd Coen tunnel
- Leak of toxic liquid (acryl-nitril) in east tunnel of 2nd Coen tunnel
- BLEVE tanker carrying liquid CO2 in east tube of existing Coen tunnel
5.3.6 Development of scenarios

From the moment the incident occurs until traffic flow is normal, the following categorization is made when describing the scenarios:

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-up and disruption</td>
<td>The events that lead to the incident.</td>
</tr>
<tr>
<td>Incident</td>
<td>The actual incident and its consequences.</td>
</tr>
<tr>
<td>Detection/alarm</td>
<td>Awareness of the incident by those present in the tunnel and the tunnel operator and/or receipt of report of incident by the tunnel operator.</td>
</tr>
<tr>
<td>Internal emergency assistance</td>
<td>Measures taken by the tunnel operator to control the situation and any self-rescue by those present in the tunnel, whether or not with the assistance of the tunnel operator.</td>
</tr>
<tr>
<td>External emergency assistance</td>
<td>Assistance by the emergency services such as the fire brigade, ambulance service and police.</td>
</tr>
<tr>
<td>End of scenario</td>
<td>The tunnel tubes are reopened (after clean-up and maintenance work, if necessary) and the flow of traffic is restored</td>
</tr>
</tbody>
</table>

The steps outlined above, which incidentally may partly occur simultaneously, are illustrated by means of a “photograph album” (see appendix), containing:

- An indication of the moment in time;
- A description of the events at the moment in time and the measures that have been taken at that moment by the operator and the emergency services;
- A graphical representation of the situation in the tunnel (tube);
- A summary of the status of the tunnel system based on the effect variables.

All scenario descriptions provide an insight into potential injury and material damage, the duration of the incident and the obstruction to traffic. A number of points of attention are also identified for the design of the tunnel and the related safety organization (communication/procedures for tunnel operator, emergency services etc.).

An example of how one of the selected scenarios may develop is shown in the text box below.
Example of scenario development: fire in cargo on goods vehicle in west tube of 2nd Coen tunnel

**Step: Run-up and disruption**
During the morning rush hour a traffic jam develops in the west tube of the 2nd Coen tunnel, in which there is a goods vehicle whose brakes overheat.

**Step: Incident**
At 200 metres from the entrance a fire breaks out in the tunnel under the loading space of the goods vehicle. The cargo catches alight (t=0) and a fire of 50MW develops.

**Step: Detection/report**
Since the SnelheidsOnderschrijdingsSysteem (slow-speed detection system) had already been activated (because of the traffic jam), the operator does not detect the fire straightaway. After t=30s the driver notices the fire, parks the vehicle on the right side at 300 metres from the tunnel entrance and tries to extinguish the fire. He does not succeed, and goes to an aid station. At t=120s the smoke detection system (sight measurement) alerts the operator and the tunnel ventilation is started up automatically.

*Point of attention* → detection could be faster by having more detection points?

The driver reports the fire via the intercom in the aid station, which automatically produces camera images of the location for the operator. A traffic jam builds up behind the fire; beyond the fire the traffic leaves the tunnel at walking pace.

**Step: Internal emergency services**
After the smoke alarm and report, the driver presses the emergency button at t=130s: both tunnel tubes are closed off, the wet fire extinguishing equipment is brought under pressure and the overpressure ventilation in the central tunnel tube is started up

*Point of attention* → ventilation must be in the same direction in both tubes.

Operator sets up diversion route. The east tube is cleared of traffic after t=180s. Operator gives escape instruction at t=140s by means of the evacuation button, and at the same time the evacuation and contour lighting is switched on.

*Point of attention* → in which languages are the evacuation instructions to be given?

The driver and the other persons immediately behind the goods vehicle run across the traffic lane towards the tunnel entrance because of the threat imposed by the fire. Most people reach safety in time, however there is one person in a vehicle close to the fire that dies from the heat, and 2 persons suffer severe burns.

At t=190s the emergency services (fire brigade, police, ambulance and salvage company) are alerted by the operator via direct lines. The 1st police surveillance car arrives within approx. 10 min. The fire brigade turns out from both sides. The ambulance comes from the nearest station.

The conditions down from the fire quickly become extremely dangerous to lethal. Ultimately 6 persons do not manage to reach an escape door in time; they do not survive (assumption). Furthermore, about 15 people are injured (breathing difficulties, burns), 5 of whom very seriously (assumption).

**Step: External emergency assistance**
The fire brigade arrives at the east tube along the service road and reports to the operator. The operator gives the number of the escape door before the accident. The fire brigade personnel, wearing protective gear, enter the tunnel at t=13 minutes via the escape doors to inspect the smoke-free zone (upwind from the fire).

*Point of attention* → emergency assistance personnel and persons trying to escape may get in each others’ way at the scene of the incident. This requires extra coordination and attention on the part of the fire brigade.

Fire hoses are connected at 50 metres on the left side of the traffic lane. Fire extinguishing begins at t=25 minutes.
Ambulance meanwhile takes care of persons escaping and treats them outside the tunnel. The two seriously injured persons are taken to hospital.

After 60 min. the fire has been extinguished. The fire brigade hands over control of the incident to the police, which set up an investigation. At t=280 minutes, the salvage firm is given permission to carry out its work. Within several hours the wreckage is transported to the dedicated area for wrecks.

In the meantime, an inspection of the east tube reveals no structural damage or damage to the systems. After consultation with the police the east tube is reopened to traffic at t=10 hours.

**Step: End scenario**
The west tube remains closed to traffic for one week for further inspection, cleaning, repairs and testing.

**End of example of scenario: fire in cargo of goods vehicle in west tube of 2nd Coen tunnel**

### 5.3.7 Conclusions and recommendations

The requirements cannot be met in all cases. These concern the following remaining risks:

- Prolonged blockages in and before the tunnel in the event of a disaster;
- The loss of the tunnel structure as a consequence of a BLEVE.

In order to improve the level of safety even further, the following main recommendations are made:

- take measures to prevent traffic jams in the tunnel;
- create alternative diversion routes for traffic;
- give extra attention to optimum ventilation design to reduce the risk of injury;
- create emergency crossings to improve accessibility for the emergency services.

Appendix: photograph album of scenario with fire in cargo of goods vehicle in west tube of 2nd Coen tunnel.
### Scenario no. 4: Fire in goods vehicle load (50MW) during morning rush hour in west tube of Second Coen Tunnel (tube no. 3)

#### Population

<table>
<thead>
<tr>
<th>Time</th>
<th>Vehicles in tube where incident occurs</th>
<th>Vehicles in other tube</th>
<th>Persons in tube where incident occurs</th>
<th>Persons in escape tube</th>
<th>No. of fatalities</th>
<th>Persons rescued</th>
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#### Atmosphere

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<thead>
<tr>
<th>Time</th>
<th>Overview</th>
<th>Ventilation in tube where incident occurs</th>
<th>Lighting</th>
<th>Escape doors towards central tunnel duct</th>
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<th>Aid station</th>
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<td>Upstream: lethal at short distance from fire (5-10m); Downstream: lethal</td>
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#### Facilities

<table>
<thead>
<tr>
<th>Time</th>
<th>Traffic lane in tube where incident occurs</th>
<th>Traffic lane in other tube</th>
<th>Fire riser</th>
<th>Speed reduction system (SOS)</th>
<th>Visibility measurement</th>
<th>Detection open escape door</th>
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#### Operator

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<th>Time</th>
<th>Reports</th>
<th>Presses CK and EK: fire brigade, police, ambulance and safety security supervisor</th>
<th>Reports</th>
<th>Presses CK and EK: fire brigade, police, ambulance and safety security supervisor</th>
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#### Emergency services

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<tr>
<th>Time</th>
<th>Communications with fire brigade; unlocks escape doors, opens barriers for fire brigade</th>
<th>Reports</th>
<th>Pressures</th>
<th>Communicates with emergency services</th>
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#### Traffic Lane in tube where incident occurs

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<thead>
<tr>
<th>Time</th>
<th>Traffic lane in other tube</th>
<th>Fire riser</th>
<th>Speed reduction system (SOS)</th>
<th>Visibility measurement</th>
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#### Emergency services clear wrecked vehicles

<table>
<thead>
<tr>
<th>Time</th>
<th>Communications with fire brigade, police, Safety&amp;Security supervisor and district manager</th>
<th>Reports</th>
<th>Pressures</th>
<th>Communicates with emergency services</th>
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#### Emergency services clear wrecked vehicles

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<th>Time</th>
<th>Communications with fire brigade, police, Safety&amp;Security supervisor and district manager</th>
<th>Reports</th>
<th>Pressures</th>
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#### End scenario

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<tr>
<th>Time</th>
<th>Communications with fire brigade, police, Safety&amp;Security supervisor and district manager</th>
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### Recap

- **Operator**
  - Reports (camera images that there is a queue in the tunnel)
  - On
  - Reports
  - Presses CK and EK

- **Emergency services**
  - Communications with fire brigade; unlocks escape doors, opens barriers for fire brigade
  - Reports
  - Pressures
  - Communicates with emergency services

- **Traffic Lane in tube where incident occurs**
  - Normal

- **Emergency services clear wrecked vehicles**
  - Communications with fire brigade, police, Safety&Security supervisor and district manager
  - Reports
  - Pressures
  - Communicates with emergency services
5.4 Dutch TUNPRIM Model – Quantitative Risk Analysis Coen Tunnel

5.4.1 Definition of the problem

The capacity of the Coen Tunnel will be increased by building a new tunnel alongside the existing one. It must be demonstrated that the level of safety is adequate in the new situation. For this purpose, a quantitative risk analysis is one of the ways that will be used to show that the personal risk for the road users is lower than 1.10^{-7} per person-kilometre and that the internal group risk is lower than 10^{-1}/N^2 per km per annum.

5.4.2 Method

The quantitative risk analysis has been carried out for the year 2020 using a spreadsheet calculation model named Tunprim (version 27-06-00). This is used to calculate the average number of victims (deaths) per annum (this is known as the expected value) and the group risk (the group risk indicates the risk of a certain number of victims in a single incident). The group risk is shown in a ‘FN curve’, the graph whereby, on a double-logarithmic scale, the frequency of exceeding the value (F) is plotted against the number of victims (N). Based on the expected value the personal risk (the risk per person-kilometre) is then calculated.

The calculation is made based on the expected traffic intensity for the year 2020.

The scenarios that are included in the calculations are:

- Injury accidents.
- Slowly developing fires (arising from technical defects) and fast-developing fires (as a result of collisions) for: cars, buses, goods vehicles with or without flammable loads.
- Release of hazardous substances: toxic liquids and flammable liquids (permitted in the Coen Tunnel) and also flammable gases, toxic gases and explosives (these however are not permitted in the Coen Tunnel).

For calculating the number of victims, the calculation model subdivides the tunnel tube into the following effect areas (see figure below):

- The safe area: it is assumed that everyone who is within a certain distance of an escape door, which will vary from scenario to scenario, will be able to escape in time.
- The fatality area: this is the area within which a percentage of those escaping will be killed. This will also vary from scenario to scenario.
- The extra area: this is the area within which extra deaths will occur in incidents where the closest escape door is blocked.
Subdivision of effect areas

The risk for each scenario (= probability x consequence) is calculated and used as the basis to calculate the expected value and the group risk.

5.4.3 Starting points for calculation:

The calculation is made for the year 2020.

Geometry:

- Tunnel length (closed section): 1st Coen Tunnel: 587m; 2nd Coen Tunnel: 740m.
- Number of traffic lanes: tube 1 (N-S): 2; tube 2 (N-S): 1 (+ emergency lane); tube 3 (tidal flow): 2; tube 4 (S-N): 3 (+ emergency lane).
- Distance between escape doors: 100m.

Traffic intensity:

In order to measure the intensities per tunnel tube, the distribution as shown in the appendix is used: this distribution is based on the statistical forecast of the total traffic volume through the Coen Tunnel in 2020. The intensities according to this distribution are so high that an I/C (Intensity/Capacity) factor ≥1 will be reached during many hours in the day.

For the percentage of buses 1% is assumed; this is an estimate and no better information is known. For the percentage of goods vehicles 10.5% is assumed, for all tubes during each hour in a 24-hour period; this is an average percentage for the lanes in both directions throughout a 24-hour period. In reality, however, the percentage of goods vehicles does fluctuate from 3% to 27%. Since the rush hour periods (with about 7% of goods traffic) are crucial for incidents with major consequences, the assumption of 10.5% for each period represents an overestimate of the risk.

For the probability of a traffic queue in the tunnel (the calculation model assumes (nearly) stationary traffic) the assumption taken is 1x per day in tube 3 (because it is assumed that each day in a North-South direction there will be a problem downstream from the tunnel where the road
forks in two directions); for the other tubes this will be 1x per 5 days (because it is assumed that
the tunnel itself forms the bottleneck and therefore a queue will form in front of the tunnel, and
only very seldom will a traffic jam develop downstream from the tunnel that then tails back into
the tunnel itself).

Incident frequencies (per vehicle-kilometre) estimated based on the existing tunnels:

- Breakdown: 6.10^{-6}.
- Accident without injury: existing Coen Tunnel 2.10^{-6} (this is the accident frequency of the
  existing tunnel as shown from earlier studies); new tunnel 1.10^{-6} (this is the average accident
  frequency in modern tunnels).
- Accident with injury: existing Coen Tunnel 2.10^{-7}; new tunnel 1.10^{-7} (the ratio between
  accidents with injury and accidents without injury is on average roughly 1 : 10).

No account has been taken of the (favourable) effect of the existence of an emergency lane in
tube 2 on the accident frequency.

**Hazardous substances:**

The starting point is that the Coen Tunnel is a category I tunnel, i.e. the transport of explosives,
flammable gases (e.g. LPG) in bulk and toxic gases in bulk is prohibited. The number of
transports of hazardous substances is based on the Risk Atlas 1997 (counts along the road ‘de
nieuwe meer-havens’).

The following applies here: transport of flammable liquids: LF1 (mainly diesel): 24500 per annum;
LF2 (mainly petrol): 13250 per annum. The calculation programme takes LF2 for flammable
liquids; LF1, because it has a 15 times lower risk of ignition, is included in the calculation by
dividing the number of transports by 15 and adding this result to LF2.

For the 2020 the arbitrary assumption is made that the number of transports of flammable liquids
will be double that of 1997; i.e. 2 x (24500/15 + 13250) = 29767 transports per annum. The
distribution of these transports in the tunnel tubes is considered the same as the distribution of
the total traffic volume in the tunnel tubes.

5.4.4 Calculation

Calculations are made for each tunnel tube.

The entry values taken, which vary for each tube, are shown in the appendix.

No distinction is made between working days and weekends. A conservative assumption is made
that there are 7 working days per week, which results in a slight overestimate of the risk.
5.4.5 Results:

Expected values (EV) per annum:

<table>
<thead>
<tr>
<th>EV</th>
<th>Tube 1</th>
<th>Tube 2</th>
<th>Tube 3</th>
<th>Tube 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>small probability, major</td>
<td>0.0423</td>
<td>0.0133</td>
<td>0.0375</td>
<td>0.1471</td>
<td>0.2402</td>
</tr>
<tr>
<td>consequences</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>extra (trapped)</td>
<td>0.0045</td>
<td>0.0020</td>
<td>0.0043</td>
<td>0.0087</td>
<td>0.0195</td>
</tr>
<tr>
<td>normal accident</td>
<td>0.3375</td>
<td>0.1530</td>
<td>0.1596</td>
<td>0.3274</td>
<td>0.9775</td>
</tr>
<tr>
<td>Total</td>
<td>0.3843</td>
<td>0.1683</td>
<td>0.2014</td>
<td>0.4832</td>
<td>1.2372</td>
</tr>
</tbody>
</table>

Comments concerning expected values

The expected values for small probability, severe consequences are largely determined by the assumption in the model that 5% of the tunnel users cannot escape by themselves and will not be assisted by other persons. As a result the incident will be fatal for them if they are close to a fire (i.e. also with very slowly developing fire as a result of technical defects, which is the case with most fires). This assumption is therefore extremely pessimistic; in fact it does not really concern a scenario with major consequences. If it is assumed that with slowly developing fires everyone can be assisted by other road users, the expected value in that case will be 0.0005 instead of 0.2402.

In determining the expected values for extra (trapped) it is assumed that with accidents involving injury followed by fire, 10% of the injured will find themselves trapped and can no longer be rescued. This is also a pessimistic assumption because when deriving the average number of fatalities for each accident involving injury account has already been taken of the deaths of those persons trapped and/or (severely) injured in the event of vehicle fires. It is in fact more a calculation of the potential number of extra victims, assuming that the chance of being able to free those trapped and/or severely injured in a tunnel is smaller compared to the open road.

The transport of hazardous substances plays a very small role in the expected value (the 4th digit after the comma).

Individual risk:

The individual risk per kilometre can be determined by dividing the expected value by the number of person-kilometres per annum.

The average number of persons per vehicle is (assumed in the calculations):

\[(0.885 \times 1.5) + (0.01 \times 22) + (0.105 \times 1) = 1.6525.\]
The number of person-kilometres per annum is: (number of vehicles per annum x tunnel length x average no. of persons per vehicle) \((25.6 + 11.6) \times 0.587 + (19.2 + 39.4) \times 0.740\) x 1.6525 = 107.7 million.

The individual risk per kilometre is therefore:

\[
1.2372 ÷ 107.7 = 0.0115 \text{ per million kilometres (}1.15 \times 10^{-8}\text{ per kilometre)}.
\]

The share of the ‘ordinary accidents’ in this calculation is \(0.9 \times 10^{-8}\) per kilometre.

**Conclusion: expected values**

The expected value is largely determined by the ‘ordinary accidents’.

The transport of hazardous substances has nearly no effect on the expected value.

The individual risk is much lower than the test criterion of \(1.10^{-7}\) per kilometre.

**Societal risk – FN Curves**

The calculated group risk is presented in a graph on a double-logarithmic scale in which the number of victims is plotted against the frequency to produce the ‘FN curve’.

The IV ‘reference line’ is the test criterion for a tunnel 740m long \((10^{-1}/N^2\text{ per km per annum)}\).

**Conclusion for societal risk:**

The societal risk for the incidents categorized as small probability, major consequences is below the test criterion of \(10^{-1}/N^2\text{ per km per annum.}\)
5.4.6 Sensitivity analysis

As an example, one of the calculations carried out with the sensitivity analysis.

Hazardous substances

In order to analyse sensitivity to the number of hazardous substances, the number of transports has been doubled.

**Expected values (EV) per annum:**

<table>
<thead>
<tr>
<th>Variant</th>
<th>Tube 1</th>
<th>Tube 2</th>
<th>Tube 3</th>
<th>Tube 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small probability, major consequences</td>
<td>0.0424</td>
<td>0.0133</td>
<td>0.0375</td>
<td>0.1472</td>
<td>0.2404</td>
</tr>
<tr>
<td>extra (trapped)</td>
<td>0.0045</td>
<td>0.0020</td>
<td>0.0043</td>
<td>0.0087</td>
<td>0.0195</td>
</tr>
<tr>
<td>ordinary accident</td>
<td>0.3375</td>
<td>0.1530</td>
<td>0.1596</td>
<td>0.3274</td>
<td>0.9775</td>
</tr>
<tr>
<td>Total</td>
<td>0.3844</td>
<td>0.1683</td>
<td>0.2014</td>
<td>0.4832</td>
<td>1.2374</td>
</tr>
</tbody>
</table>

**Conclusion of expected values:**

With the doubling of the number of vehicles carrying hazardous substances, the expected value (and with it the personal risk) hardly changes at all.

Societal risk:

The graph below shows the change to the societal risk (for the 4 tubes together) if the number of transports with hazardous substances is doubled.
Conclusion for societal risk:

The effect of doubling the number of transports with hazardous substances can be clearly seen in the societal risk. For scenario's with a large number of victims (from about 10 victims), the frequency doubles.

The societal risk for incidents with small probability/major consequences where the number of transports with hazardous substances is doubled still remains below the test criterion of $10^{-1}/N^2$ per km per annum.

Appendix: Input values

**Tube 1:**

2 traffic lanes.

Intensity per day: 70171 → 25.6 million per annum.

10 rush hours at 6.13% of the 24-hour intensity per hour (= 4300);

6 night hours at 1% of the 24-hour intensity per hour (= 702);

Likelihood of queues: Once every 5 days.

Hazardous substances: $29767 \times 70171 \div 262700 = 7951$ per annum.

**Tube 2:**

1 traffic lane (+ emergency lane).

Intensity per day: 31854 → 11.6 million per annum.

15 rush hours at 5.65% of the 24-hour intensity per hour (= 1800);
6 night hours at 1% of the 24-hour intensity per hour (= 319);
Likelihood of queues: Once every 5 days.
Hazardous substances: \(29767 \times 31854 \div 262700 = 3609\) per annum.

**Tube 3:**

2 traffic lanes (tidal flow).
Intensity per day: 52595 \(\rightarrow\) 19.2 million per annum.
7 rush hours at 8.18% of the 24-hour intensity per hour (= 4300);
Closed for 9 night hours;
Likelihood of queues: Once a day (direction south).
Hazardous substances: \(29767 \times 52595 \div 262700 = 5960\) per annum.

**Tube 4:**

3 traffic lanes (+ emergency lane).
Intensity per day: 108080 \(\rightarrow\) 39.4 million per annum.
12 rush hours at 6.11% of the 24-hour traffic intensity per hour (= 6600);
6 night hours at 1% of the 24-hour intensity per hour (= 1081);
Likelihood of queues: Once every 5 days.
Hazardous substances: \(29767 \times 108080 \div 262700 = 12247\) per annum.
5.5 Italian Risk Analysis for Road Tunnels

5.5.1 Definition of the problem

The Table shown in point 2.19 of Annex 1 to European Directive 2004/54/EC highlights ten types of tunnels whose reference values, for the safety parameters (Annexe 1- § 1.1) length (L) and traffic volume (A.A.D.T.), comply with ten specific sets of minimum safety requirements.

The Table below summarizes the ten types of tunnel.

<table>
<thead>
<tr>
<th>Monodirectional tunnel</th>
<th>500 &lt;L&lt;1000</th>
<th>L&gt;1000</th>
<th>500&lt;L&lt;1000</th>
<th>1000&lt;L&lt;3000</th>
<th>L&gt;3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>T &lt; 2000 v/l·d</td>
<td>I</td>
<td>II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T &gt; 2000 v/l·d</td>
<td></td>
<td>III</td>
<td>IV</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Bidirectional tunnel</td>
<td>500 &lt;L&lt;1000</td>
<td>L&gt;1000</td>
<td>500&lt;L&lt;1000</td>
<td>1000&lt;L&lt;3000</td>
<td>L&gt;3000</td>
</tr>
<tr>
<td>T &lt; 2000 v/l·d</td>
<td>VI</td>
<td>VII</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000 &lt; T &lt; 10000 v/l·d</td>
<td>VIII</td>
<td>IX</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The European Directive does not explicitly fix any upper limit for the safety parameters as length (L) and traffic volume (AADT).

An analysis of the rate of road accidents versus traffic volume, carried out on the basis of data relative to the Italian motorway network, shows that the regression curve presents an abrupt change in slope:

- for monodirectional tunnels the critical value of the traffic volume is 15000 vehicles/ lane day.

The recommendation in § 2.1 of Annexe 1 to the European Directive suggests:

- for bidirectional tunnels the traffic volume value of 10000 vehicles/ lane day.

A similar analysis of the casualty and fatality rate due to fires in the tunnel versus tunnel length, carried out on the basis of data contained in the PIARC document (1999), and updated to 2005, has led to the identification of the following reference values:

- for monodirectional tunnels the safety parameter limit value for length (L) is 5000 m;
- for bidirectional tunnels the safety parameter limit value for length (L) is 3000 m.

In the framework of a performance-based approach to the design of transport systems, IEC Regulation n° 61508 attributes specific performance functions to the safety subsystems (i.e. Annexe 1, § 1.2). Moreover, each safety subsystem is characterized by a specific level of integrity expressed in terms of reliability.

The above observations suggested the introduction of the following auxiliary concepts.
Virtual tunnel: a tunnel that wholly complies with the provisions of the European Directive in terms of both safety parameters (Annexe 1, § 1.1) and minimum requirements (Annexe 1, § 1.2) and for which the safety subsystems that implement the minimum requirements are characterized by ideal reliability and efficiency.

Theoretical tunnel: an existing tunnel, or its upgrading design, or a final design of the new tunnel, where not all the safety requirements (Annexe 1, § 1.2) are adopted, but it behaves according to ideal reliability and efficiency.

Actual tunnel: an existing tunnel, or its upgrading design, or a final design of the new tunnel, where not all the safety requirements (Annexe 1, § 1.2) are adopted but it behaves according to actual reliability and efficiency as per best practices.

The developed risk analysis procedure adopts the F-N plane for representing risk. The straight line tangent envelope to the complementary cumulated distributions (C.C.D.) derived from the Event Tree Analyses associated with virtual tunnels defines a reference limit condition on the risk representation plane.

According to the risk analysis presented below, the virtual tunnels are used as references in determining the risk level of actual tunnels.

The presented risk analysis procedure assumes the performance-based design of the structure as the characterizing feature of the tunnel safety design.

5.5.2 Description of the tunnel systems analysed

The presented case study concerns:

- the application of the proposed risk analysis procedure to types V and X of virtual tunnels in order to identify on the Plane F-N, a limit condition defined as the straight line tangent envelope to the complementary cumulated distributions associated with virtual tunnels;

- the application of the proposed risk analysis procedure to three existing tunnels of the Italian road network that present various deficits with regard to the minimum safety requirements (Annexe 1, § 1.2).
The tables presented below give the characterising values for virtual tunnels types V and X.

<table>
<thead>
<tr>
<th>Name</th>
<th>Tunnel Type V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel System</td>
<td>Monodirectional</td>
</tr>
<tr>
<td>Tunnel Length [m]</td>
<td>5000</td>
</tr>
<tr>
<td>Lanes</td>
<td>2</td>
</tr>
<tr>
<td>Traffic (annual average daily traffic-v/d. l.)</td>
<td>15000</td>
</tr>
<tr>
<td>Heavy goods vehicles [%]</td>
<td>15</td>
</tr>
<tr>
<td>Emergency Exits Distance [m]</td>
<td>500</td>
</tr>
<tr>
<td>Minimum Requirements Deficit</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Tunnel Type X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel System</td>
<td>Bidirectional</td>
</tr>
<tr>
<td>Tunnel Length [m]</td>
<td>3000</td>
</tr>
<tr>
<td>Lanes</td>
<td>1</td>
</tr>
<tr>
<td>Traffic (annual average daily traffic-v/d. l.)</td>
<td>10000</td>
</tr>
<tr>
<td>Heavy goods vehicles [%]</td>
<td>15</td>
</tr>
<tr>
<td>Emergency Exits Distance [m]</td>
<td>500</td>
</tr>
<tr>
<td>Minimum Requirements Deficit</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Autostrade per l’Italia 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel System</td>
<td>Monodirectional</td>
</tr>
<tr>
<td>Tunnel Length [m]</td>
<td>3200</td>
</tr>
<tr>
<td>Lanes</td>
<td>2</td>
</tr>
<tr>
<td>Traffic (annual average daily traffic-v/l·d)</td>
<td>5500</td>
</tr>
<tr>
<td>Heavy goods vehicles [%]</td>
<td>10</td>
</tr>
<tr>
<td>Emergency Exits Distance [m]</td>
<td>700</td>
</tr>
<tr>
<td>Minimum Requirements Deficit</td>
<td>1-Emergency Exits Distances. 2- Water supply. 3-Drainages.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>ANAS 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel System</td>
<td>Monodirectional</td>
</tr>
<tr>
<td>Tunnel Length [m]</td>
<td>3200</td>
</tr>
<tr>
<td>Lanes</td>
<td>2</td>
</tr>
<tr>
<td>Traffic (annual average daily traffic-v/l·d)</td>
<td>12000</td>
</tr>
<tr>
<td>Heavy goods vehicles [%]</td>
<td>10</td>
</tr>
<tr>
<td>Emergency Exits Distance [m]</td>
<td>450</td>
</tr>
<tr>
<td>Minimum Requirements Deficit</td>
<td>-</td>
</tr>
</tbody>
</table>
5.5.3 Quantitative Probabilistic Risk Analysis (SPQR)

Steps of the Procedure

The essential steps in the proposed risk analysis procedure, described in detail in chapter 4, are:

i. Characterization of the tunnel structure  
   Structural measures, systems measures

ii. Identification of the sources of hazard and corresponding incident rate  
   Passenger cars, coaches, heavy goods vehicles

iii. Identification of potential hazards  
   Mechanical-thermal, chemical-thermal

iv. Characterization of Hazard Scenarios  
   Probability of triggering events, energetic characterization of sources,  
   event tree analysis (ETA)

v. Quantification and zoning of the hazard flow in the tunnel  
   Field of airflow, temperature, concentration of combustion products (models for mass  
   transport and energy)  
   Size of the lethal hazard zones (effective fractional dose)

vi. Quantification of the damage  
   Exposed population (models of vehicle queues)  
   Fatalities (models for the evacuation process)

vii. Risk estimation and risk representation  
   Damage Expected Values, Complementary Cumulated Distributions (C.C.D.)

viii. Risk evaluation  
   Comparison of Complementary Cumulated Distributions (C.C.D.) to predefined reference  
   terms and acceptability criteria

5.5.4 Event Tree Analysis

The Event Tree represents the risk estimation tool adopted in the proposed procedure. It includes  
the impact that the safety subsystems, expressed in terms of reliability and efficiency, have on the  
evolution of the hazard flow in the tunnel system along an emergency scenario (S).
The diagram presented below shows the Complementary Cumulated Distributions (C.C.D.) for virtual tunnels of types V and X.

The straight line shown in the diagram, represents the envelope that is tangent to the C.C.D. associated with virtual tunnels, and it defines a reference limit condition.

The diagram presented below shows the Complementary Cumulated Distributions (C.C.D.) for virtual tunnels of types V and X.

The straight line shown in the diagram, represents the envelope that is tangent to the C.C.D. associated with virtual tunnels, and it defines a reference limit condition.

The tree diagrams below show the C.C.D. for three existing tunnels of the Italian road network.

Virtual, Theoretical, Actual C.C.D. of the “Autostrade 1” Tunnel
Virtual, Theoretical, Actual C.C.D. of the “ANAS 1” Tunnel

Virtual, Theoretical, Actual C.C.D. of the “ANAS 2” Tunnel
5.5.5 Conclusions

The results of the risk analysis obtained according to the proposed procedure can be a
decisional-making tool for the Administrative Authority (Article 4 European Directive). It can be
completed and supplemented by appropriated criteria for both risk relative comparisons and the
adoption of an absolute acceptability limit eventually suggested by the Government Authorities.
The absolute acceptability limit can be located, for instance, two decades above the identified
reference line.
5.6 United Kingdom

5.6.1 Definition of the problem

This case study illustrates the approach taken for risk analysis on a recent road tunnel project in the UK. In practice, the approach varies according to the project, the objectives and the organisations involved.

The case study is based on a new road tunnel project in Southeast England. The route currently comprises a combination of single 60 mph and 40 mph carriageways between sections of dual two-lane 70 mph carriageways. The proposed scheme would replace the single carriageway sections with a 1.9 km long tunnel comprising twin bores, each normally carrying uni-directional traffic, linked by cross passages at intervals in the order of 100m.

5.6.2 Design Context of risk analysis

The tunnel design is based upon Highways Agency standards and guidance, notably BD 78/99 ‘Design of Road Tunnels’, and relevant British standards. Consideration is given to PIARC guidance but this has no regulatory status in the UK. The route does not lie on the Trans-European Road Network and is therefore not subject to the European Directive 2004/54/EC on “minimum safety requirements for tunnels in the Trans-European Road Network”.

The fundamental objectives for tunnel safety are:

- to ensure the safety of the public using the tunnel, of personnel maintaining the facilities, and of the emergency services attending an incident in the tunnel;
- to minimise the likelihood of damage occurring to the tunnel and thereby minimise the resulting disruption of traffic operations.

The design takes into account the different operational modes of the tunnel:

- normal traffic operations;
- contraflow (bi-directional) traffic operations in a single bore, when the other bore is closed for routine maintenance or due to an incident.

The design takes into account the range and nature of possible incidents which could occur in the tunnel. These include vehicle breakdowns, collisions, traffic congestion, vehicle fires; and incidents involving the transport of dangerous goods.

In accordance with BD 78/99, a Tunnel Design and Safety Consultation Group (TDSCG) was set up at the feasibility stage and subsequently met at regular intervals to review the tunnel safety strategy and proposed design solutions. The TDSCG comprises appropriate levels of
representation from the various stakeholders, including the emergency services. The key objectives of the TDSCG are:

- to agree the basic configuration of the tunnel and the functionality of plant and equipment to be installed;
- to establish agreed written procedures for the safe operation and maintenance of the tunnel, its approach roads and services buildings.

The methodology used for evaluating risks depends on the issue being considered, as illustrated below. In some cases, probabilistic risk analysis is used to inform the decision making process, as when considering the justification for installing a tunnel suppression system. Alternatively, scenario analysis may be used, for example, to evaluate smoke conditions in the event of a fire occurring during contraflow (bi-directional) traffic operations. In other cases, the risks and choice of risk reduction measures are considered intuitively without formal analysis.
### 5.6.3 Definition of the system

The following data describing the tunnel and its characteristics are an important part of the input data of the risk model:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel configuration:</td>
<td>Twin bore tunnel</td>
</tr>
<tr>
<td>Tunnel length:</td>
<td>1900 m</td>
</tr>
<tr>
<td>Tunnel cross-section:</td>
<td>65 m²</td>
</tr>
<tr>
<td>Emergency exits:</td>
<td>every 100 m</td>
</tr>
<tr>
<td>Traffic (annual average daily traffic):</td>
<td>35,400 (forecast)</td>
</tr>
<tr>
<td>Heavy goods vehicles (HGVs):</td>
<td>10% (forecast)</td>
</tr>
<tr>
<td>Dangerous goods vehicles:</td>
<td>5.4% of HGVs (forecast)</td>
</tr>
<tr>
<td>Ventilation:</td>
<td>Longitudinal (jet fans)</td>
</tr>
<tr>
<td>Safety systems:</td>
<td>100% CCTV coverage</td>
</tr>
<tr>
<td></td>
<td>Automatic incident detection</td>
</tr>
<tr>
<td></td>
<td>Automatic fire detection</td>
</tr>
<tr>
<td></td>
<td>Radio voice break-in</td>
</tr>
<tr>
<td></td>
<td>Public address system</td>
</tr>
</tbody>
</table>

There would be an overnight (8 hours) maintenance closure every month. The forecast duration, traffic flows and annual mileage travelled in the tunnel during normal and contraflow traffic operations is as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Normal traffic</th>
<th>Contraflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of traffic mode (days/year):</td>
<td>361</td>
<td>4 (= 12 x 8 hours)</td>
</tr>
<tr>
<td>Traffic flow (veh/day):</td>
<td>35,400</td>
<td>2,832 (equivalent)</td>
</tr>
<tr>
<td>Annual tunnel mileage (veh-km/yr):</td>
<td>24,146,340</td>
<td>21,523</td>
</tr>
<tr>
<td>Overall fraction of tunnel mileage (-):</td>
<td>0.999</td>
<td>0.001</td>
</tr>
</tbody>
</table>

### 5.6.4 Qualitative risk analysis

A qualitative risk analysis was carried out at an early stage in the design to identify and assess the risks during tunnel operations. The Risk Priority Number (RPN) method described in BD 78/99 was used:

- Hazards are identified, starting from a list given in BD 78/99 which includes, for example, vehicle-related hazards (such as collisions and fires), non-vehicle hazards (such as pedestrians in the tunnel), equipment failure and maintenance-related hazards, and weather hazards.
Each hazard is assigned an ‘event probability’ category and an ‘event impact’ category from lists given in BD 78/99, giving a score for each.

The tolerability of risk (‘acceptable’, ‘tolerable’, ‘undesirable’ or ‘intolerable’) is indicated by the Risk Priority Number = event probability x event impact.

A list of about forty credible hazards was compiled. None of the associated risks was considered to be ‘intolerable’ and most were rated as ‘tolerable’ or ‘acceptable’. A number of risks were categorised as ‘undesirable’, requiring actions to ensure that the risks are greatly reduced:

- vehicle collision with a stationary vehicle;
- head-on collision between vehicles during contraflow traffic operations;
- serious fire involving a heavy goods vehicle (HGV).

5.6.5 Quantitative risk analysis

Quantitative risk analyses were carried out for traffic accidents and tunnel fires. The risks of dangerous goods incidents were also examined in order to determine whether there would be any significant safety benefit gained by diverting DGVs along an alternative route that avoided the tunnel.

Traffic accidents and fires

Traffic accidents occur along the existing route at frequencies that reflect the local nature of the road and traffic conditions. For the dual carriageway sections of the existing route, the accident rate currently varies between 9 and 13 personal injury accidents per 100 million vehicle-kilometres (PIA/100 mvkm) giving an average rate of 11 PIA/100 mvkm. This is slightly higher than the UK average for motorways. The single carriageway sections have an accident rate of 55 PIA/100 mvkm, which is close to the national average of 51 PIA/100 mvkm for roads of the same type.

It is expected that the tunnel accident rates would be lower than for an open section of the route. This is because the tunnel would provide a dry, sheltered and well-lit environment for driving, in contrast to an open road which is exposed to the weather and is unlit. However, in the absence of supporting evidence for UK tunnels, it is assumed pessimistically that the accident rates for the tunnel would be the same as for the adjacent open sections.

In the absence of reliable statistics for tunnel fires in the UK, estimates of fire frequencies are generally obtained either from international tunnel fire statistics or derived from vehicle fire statistics for the UK as a whole.

The number of fatalities from traffic accidents is estimated from national statistics, assuming no difference in accident rates between open and tunnel routes. Estimates of the numbers of
fatalities from tunnel fires have been derived from published information on serious road tunnel fires that have occurred world-wide. The results are summarised below.

<table>
<thead>
<tr>
<th>Type of fatal incident</th>
<th>Incidents per year</th>
<th>Fatalities per incident</th>
<th>Fatalities per 120 years</th>
<th>Expected value (fatalities/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal operations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fatal traffic accident</td>
<td>8.0E-02</td>
<td>1.2</td>
<td>11.5</td>
<td>9.6E-02</td>
</tr>
<tr>
<td>'moderate' fire</td>
<td>1.5E-02</td>
<td>0.2</td>
<td>0.4</td>
<td>3.0E-03</td>
</tr>
<tr>
<td>'severe' fire</td>
<td>5.0E-03</td>
<td>2.0</td>
<td>1.2</td>
<td>1.0E-02</td>
</tr>
<tr>
<td><strong>Contraflow operations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fatal traffic accident</td>
<td>1.1E-04</td>
<td>1.1</td>
<td>0.01</td>
<td>1.2E-04</td>
</tr>
<tr>
<td>'moderate' fire</td>
<td>2.1E-05</td>
<td>1.0</td>
<td>0.003</td>
<td>2.1E-05</td>
</tr>
<tr>
<td>'severe' fire</td>
<td>7.2E-06</td>
<td>10</td>
<td>0.009</td>
<td>7.2E-05</td>
</tr>
</tbody>
</table>

The value of 11.5 fatalities due to traffic accidents is based on the predicted average accident rate of 11 PIA/100 mvkm for the scheme. It is expected that the tunnel accident rates would actually be lower than the average for open sections of the route, due to the dry, sheltered and well-lit environment of the tunnel. For the dual carriageway sections of the existing route that are representative of the high standard design proposed for this scheme, the accident rate actually varies between 9 and 13 PIA/100 mvkm. This range of accident rates corresponds to between 9.4 and 13.6 fatalities over 120 years. It is predicted that fires would increase the risks by 1.6 fatalities per 120 years, above the estimated 11.5 fatalities due to traffic accidents, giving a total of 13.1 fatalities per 120 years.

**Dangerous goods**

The risks associated with dangerous goods incidents were assessed using the OECD-PIARC DG-QRA model. Specifically, the DG-QRA model was used to help answer two questions:

- Should dangerous goods traffic be permitted to use the tunnel or diverted along a long distance alternative route?
- Assuming that one bore of the tunnel would sometimes need to be closed for short periods for maintenance or following an emergency, should all traffic from the closed carriageway be diverted along a local alternative route or should the other bore be operated in contraflow mode?
5.6.6 Scenario analysis

Deterministic analysis was used for selected scenarios to evaluate the emergency ventilation and conditions for evacuation and intervention by the emergency services during contraflow traffic incidents. In this case, CFD simulations were carried out to predict the movement of smoke and heat in the event of a fire under contraflow (bi-directional) traffic conditions, when one bore is closed for maintenance.

A one-dimensional (1-D) tunnel fire and evacuation model was also used to examine certain issues arising during the design development, such as the spacing between cross passages.

This model takes account of:

- tunnel geometry;
- fire growth and smoke production;
- smoke spread under varying airflow conditions (stratified layer or fully mixed);
- evacuation along the tunnel;
- effects of heat and smoke toxicity on people escaping from the incident.

For both modelling approaches, the effects of heat and smoke on people are estimated from using the concept of Fractional Effective Dose (FED) as described in the ISO technical standard (ISO/TS 13571, 2002) on “Guidelines for the estimation of time available for escape using fire data”.

5.6.7 Results of risk evaluation

The risk analysis results showed that the risk in the tunnel due to traffic accidents and fires would be less than the traffic accident risk along some open dual carriageway sections of the route. Overall, it was concluded that the level of public safety in the tunnel would be comparable to that along the adjoining dual carriageway sections of the route.

For dangerous goods transport, it was found that with HGV fire risks included in the analysis, there was no significant difference between the overall risks for the tunnel route and an alternative long distance route. For emergency local diversions, it was found that diverting HGVs and DGVs along a local alternative route would lead to slightly lower societal risks compared to
contraflow operations in the non-incident bore, but the absolute level of risk would be low for both options.

The scenario analysis, involving CFD modelling of vehicle fires occurring under contraflow traffic operations, was used to support decisions on how to control the longitudinal ventilation system.
5.7 DG QRA MODEL from OECD/PIARC

5.7.1 Definition of the Problem

In an existing tunnel the transport of dangerous goods is permitted without restrictions since it is opened to traffic. In accordance to recent regulations, a risk analysis regarding dangerous goods transport is performed and implemented in the safety documentation.

5.7.2 Definition of the System

The following data describing the tunnel and its characteristics are an import part of the input data of the risk model:

<table>
<thead>
<tr>
<th>Tunnel system: Twin bores tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>East bore</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Width</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Section</td>
</tr>
<tr>
<td>Camber</td>
</tr>
<tr>
<td>Longitudinal Gradient</td>
</tr>
<tr>
<td>Drainage system</td>
</tr>
</tbody>
</table>

Emergency exits: every 90m
Traffic (annual average daily traffic): 155,000 (2015 traffic forecast)
Heavy goods vehicles: 6.8% (of overall traffic)
Dangerous goods vehicles: 1.9% of heavy goods vehicles (i.e. 200 DG vehicles per day)
Buses: 0.4% (of overall traffic)
Ventilation: Cross ventilation with smoke extraction openings with a capacity of 150 m³/s (in accordance with Austrian design guidelines)

Automatic incident detection system: To be implemented
5.7.3 Intrinsinc Risk Calculation (IR)

This calculation is done with using the DG QRA model.

Given possible variability of initial meteorological conditions, IR value ranges from 0.0008 to 0.0014.

This last value is higher than 0.001 limit for which a QRA study is required comparing alternative routes (see chapter 3.2.7). Therefore, a quantified comparison between the tunnel route and 2 alternative routes has been performed.

5.7.4 Comparative QRA study

Compared routes

The compared routes are represented on the following map:

Tunnel route and alternative route number 1 are compared between points A1 and B. Tunnel route and alternative route number 2 are compared between points A2 and B.
Results of Risk Calculation

Comparison between Tunnel route / Alternative route #1

Regarding comparison between tunnel route and alternative route #1 the following F/N curves have been obtained:

The EV (Expected Value) corresponds to the yearly expected number of victims due to dangerous goods transported through the considered route.

The resulting ratio of the EV's of the Tunnel Route and the Alternative Route #1 is thus about 1/1.4.
Comparison between Tunnel route / Alternative route #2

Regarding comparison between tunnel route and alternative route #2 the following F/N curves have been obtained:

The resulting ratio between Tunnel Route and Alternative Route #2 Expected Values (EV) is thus about 1/0.9.

Results of Risk Evaluation

When comparing two routes, it is generally considered that, if:

\[
\frac{EV_1}{EV_2} < 3 \quad \text{other criteria are required to make a decision,}
\]

3 < \(\frac{EV_1}{EV_2}\) < 10 a sensitivity study on main parameters is required to conclude,

\(\frac{EV_1}{EV_2} > 10\) the route which results in \(EV_2\) value should be favoured.

Therefore, this QRA comparison in both cases shows no significant difference between the 2 compared routes.

Other criteria investigated

Generally, the following criteria should be considered when the QRA study does not allow a clear choice between routes:

- Risk aversion,
- Accidents without involvement of hazardous material,
- Route vulnerability from economic and environmental points of view.
In the present case, the second criterion allows to make a choice. The following table presents the results from risks calculations derived from accidents without involvement of transported dangerous goods:

<table>
<thead>
<tr>
<th>Routes</th>
<th>QRA model comparison</th>
<th>Accidents without DG involved</th>
<th>Global Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV Tunnel Route</td>
<td>9.4E-03</td>
<td>3.8E-03</td>
<td>1.3E-02</td>
</tr>
<tr>
<td>EV Alternative Route #1</td>
<td>1.3E-02</td>
<td>4.0E-02</td>
<td>5.3E-02</td>
</tr>
<tr>
<td>Ratio</td>
<td>1.4</td>
<td>10.6</td>
<td>4.0</td>
</tr>
<tr>
<td>EV Tunnel Route</td>
<td>5.0E-03</td>
<td>1.0E-03</td>
<td>6.0E-03</td>
</tr>
<tr>
<td>EV Alternative Route #1</td>
<td>4.5E-03</td>
<td>1.9E-02</td>
<td>2.4E-02</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.9</td>
<td>19.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Reported results in this table show that risks due to road accidents without involvement of dangerous goods are significantly higher (more than a factor of 10) on alternative routes than on tunnel route.

**Therefore, the conclusion of this study is that dangerous goods transport must be maintained on tunnel route.**
6. Conclusions and Recommendations

6.1 Summary and General Conclusions

The severe tunnel fires in the past years in different European road tunnels pointed out, to which specific dangers – mainly related to confinement – road tunnel users can be exposed in comparison to open roads. In the context of road tunnel safety management, several additional safety measures and precautions are planned in order to mitigate these dangers and the related risks. Besides the implementation of safety measures according to guidelines and standards, the application of risk-based approaches in the process of tunnel safety management recently gained in importance. For instance in some circumstances, the European Directive on minimum safety requirements for tunnels in the trans-European road network [15] requires the use of risk analysis considering the particular risk relevant influence parameters for a specific tunnel.

In the context of road tunnel safety management a broad range of qualitative and quantitative methodology components (see chapter 3) is available for the three elements of a risk-based approach, i.e. risk analysis, risk evaluation and planning of safety measures. All the presented methodology components exhibit specific advantages and disadvantages and the investigation has demonstrated, that most of the methods used in practice are a combination of various methodology components. But none of these methodology components or a combination of them can claim to be the most suitable in practical use in the context of road tunnel safety management. Hence the choice of the methodology components should be done by considering the respective advantages/disadvantages in the context of a specific situation. Therefore the selection of the right method to investigate given issues has to match the specific problem, the required depth of assessment and the available resources. It has to be taken into account that quantitative methods (e.g. simulations or statistical analysis) are normally more complex and therefore imply more effort for the analysis than qualitative methods (e.g. expert judgements). Furthermore, quantitative methods require specific quantitative input data which may not be available or may not show the quality required. In addition, it has to be considered that methodology components cannot be chosen arbitrarily: Certain components for risk evaluation require specific components for risk analysis.

As the case studies in chapter 4 illustrate, in practice, several different methodology components are chosen for an analysis and they often can not be distinguished clearly because different methodology components are commonly combined. For instance, expert judgments and/or assumptions are often used in the context of quantitative approaches to compensate for lack of data, e.g. if there are insufficient data for a statistical analysis.

These findings highlight clearly, that the possibilities for the harmonization of methods of risk analyses for road tunnels are limited; the problems to be investigated, tunnel infrastructure and local boundary conditions, traffic situation, national characteristics,
regulations and laws and even the behaviour of the users are so different that one unique method cannot cover all relevant issues in an adequate way;

However, in future it seems to be possible to develop universally applicable quality criteria for risk analysis for road tunnels. The standardization of some specific elements of risk analysis (eg. Characteristics of relevant fire scenarios like fire size and development) seems to be achievable as well, without limiting the flexibility of the methods.

Experience shows, that the question of risk evaluation and the definition of what level of risk is acceptable, is a significant and debatable part of the risk management. In this context, a valuation of the different aspects of risk has to be included. In the framework of this report the question of risk evaluation has only been treated from a methodical point of view (to demonstrate which ways of risk evaluation are feasible given a specific method of risk analysis being used). The problems, chances and restrictions related to different strategies of risk evaluation are not discussed. This item should be addressed in more detail in future. However, it can be concluded from the practical methods investigated, that the character of the EU-Directive favours approaches based upon relative comparison.

The investigation of several practical methods and their application in case studies clearly demonstrate, that the process of a risk-based road tunnel safety management allows a structured, harmonised and transparent assessment of risks for a specific tunnel including the consideration of the relevant influence factors. Moreover, it allows coming up with the best additional safety measures in terms of risk mitigation, including the possibility, to take cost/benefit – criteria into account. But in all countries the risk based approach is used as a completion to prescriptive regulations or guidelines.

Hence there is no doubt, that the risk-based approach in the context of road tunnel safety management is an appropriate and valuable supplement to the implementation of measures to respect the requirements of standards and guidelines.

6.2 Some Recommendations for the practical use of Risk Analysis

Based upon the results of the work of working group 2 the following recommendations for the practical use of risk analysis can be given:

- Be aware that whatever method you choose, you are always using a model which is a more or less extensive simplification of the real conditions and which can never be able to predict the course of a real event but which enables you to make decisions on a sound and comparable basis

- select the best method available for a specific problem; the present report provides a survey of well-tried methods for various problems
- when selecting a method for a risk analysis you should also consider the way how to evaluate the results – the method of risk analysis and the strategy of risk evaluation are not independent!

- whenever possible use specific data for quantitative methods; if specific data is not available at least check the origin of the data you are intended to use (are the conditions referring to infrastructure, traffic etc. similar to your situation?); be aware that in a risk model specific features may be included, which are not valid for your tunnel!

- For that reasons risk analysis should only be performed by experts with sufficient experience who also dispose of background information about the methods they use

- Be aware that the result of a quantitative risk analysis must be interpreted as order of magnitude and not as precise number; risk models inevitably deliver fuzzy results; risk evaluation by relative comparison (eg. Of various safety measures or of an existing state to a reference state of a tunnel ) may reduce unsteadiness of results

6.3 Outlook and Need for further Investigations

It can be expected that in near future risk analysis will become in many countries a commonly used tool for risk assessment of road tunnels; at the same time the experience in application of risk analysis and the need for an exchange of experience at European/international level will increase; this process should result in a continuous improvement of existing or newly developed methods or models;

The European Directive on the minimum safety requirements for road tunnels [15] also defines requirements for the systematic collection and analysis of accident and incident data so that in future a more comprehensive and more informative data basis should be available than today.

As far as research work and further methodical developments are concerned the efforts should focus on the following issues:

- in terms of harmonization: development of universally applicable quality criteria for risk analysis for road tunnels and standardization of some specific elements of risk analysis

- more thorough investigation of possible strategies of risk evaluation, including recommendations for their application
7. References

[14] NACHDIPLOMKURS „Risiko und Sicherheit“ 1997, ETHZ, HSG, EPFL, Mathematische Modelle zur Beschreibung, Darstellung und Interpretation von Risiken; hans A. Merz, Ernst Basler & Partner AG, Zürich

8. Enclosures

Appendix 1: Overview of Methodology Components – detailed Description
Appendix 2: Questionnaire
APPENDIX 1: OVERVIEW OF METHODOLOGY COMPONENTS – DETAILED DESCRIPTION

In the following, the relevant characteristics of a selection of the most important methodology components are summarised. According to the procedure described in chapter 3.1, they are arranged into the three steps of safety management: risk analysis, risk evaluation and planning of safety measures. For each methodology component the following characteristics are described ([12], [13]):

- Methodology component
- Description
- Scope
- Advantages / disadvantages

### SELECTION OF METHODOLOGY COMPONENTS FOR RISK ANALYSIS

<table>
<thead>
<tr>
<th>Methodology component</th>
<th>Description</th>
<th>Scope</th>
<th>Advantages / disadvantages</th>
</tr>
</thead>
</table>
| Expert judgment       | - Expert judgment is an estimation of several experts from the field of activity concerned to a particular question. The estimation reflects the knowledge and the experience of these specialists  
- Expert judgment can be of qualitative and quantitative kind.  
- Expert judgment can be the basis of further methods (e.g. brainstorming or Delphi method) | - Assessment of frequency, consequence and risk  
- Comparative evaluation of frequency, extent and risk  
- Evaluation of safety measures, estimation of costs, estimation of possible risk reduction due to safety measures  
- Suitable for estimation in subsystems or in case of lack of data bases  
- Check of plausibility | + Low complexity  
- The "quality" of estimation depends on the experience and knowledge of the experts  
- Expert judgments can be strongly affected by (current, individual) experiences  
- Danger of ignoring certain aspects ("it cannot be, what may not be.")  
- Comprehensive survey missing |
| What-If method         | - The What If-method is a creative method, which is accomplished in a team.  
- One proceeds from the question "What will happen if...?". Each member formulates specific questions, which are answered in the team. In this way, possible endangerments during a process are recognised. Furthermore, possible counteractive measures are formulated. | - Identification and analysis of hazards  
- Definition of safety measures  
- Instrument for planning or improvement of a system  
- Rather suitable for simple causal correlations, problematic for complex systems | + Low complexity  
+ Detection of weak points in a system  
- The quality of the results depends directly on the composition of the team.  
- Substantial elements of a system are sometimes not detected.  
- Not applicable for comparative safety assessments |
<table>
<thead>
<tr>
<th>Methodology component</th>
<th>Description</th>
<th>Scope</th>
<th>Advantages / disadvantages</th>
</tr>
</thead>
</table>
| **Checklist procedure** | - The checklist procedure is a simple, purely qualitative method for a first inspection of a system. It is frequently used in combination with other methods, or as a basis for other analysis methods. 
- Checklists contain a list of questions. On the basis of checklists a system is analysed. | - Analysis of technical systems and processes. 
- Identification and analysis of dangers 
- Suitable for routine/repetitive analyses. 
- The checklist procedure is widespread in the chemical industry. | + Low complexity 
+ The use of the checklist procedure has the advantage of a simple structure and broad application possibilities. 
+ The checklist procedure gives a first overview of potential safety problems 
- The more complex the analysed system is, the more complex become the checklists. It remains questionable whether all important aspects of a system are recognised or not. 
- New problems, as they can result for processes in combination with specific conditions, are often identified only insufficiently. Subsequent events are also hardly recognised. 
- The quality of the analysis depends directly on the completeness of the checklist. It also strongly depends on the knowledge of the accomplishing persons. |
| **Safety review** | - A goal of a safety review is the examination of a system, regarding weak points and specific dangers. 
- Analysing a system/plant in discussion with operating personnel to identify possible dangers and/or weak points. The procedure includes an inspection of the plant. | - Weak point analysis 
- Evaluation of safety measures 
- Improvement of an existing system, no planning instrument | + Small effort in order to get first results. 
+ The co-workers who take part in the interviews can become conscious of the existing dangers (training effect). 
+ Procedure is related to practice 
- No information about the relevance of a specific danger and/or weak points 
- Not applicable for comparative safety assessments |
| **Statistical data analysis** | - Analysis of collected data (experience) 
- The analysis can be made for frequency and consequences. Having sufficient data, information about distribution parameters, standard deviations, etc. can be estimated. 
- Beside the data analysis, there is always the need of an interpretation. | - Suitable for systems with the following peculiarities: 
  o Well-established technology 
  o Sufficient event data 
- The results of the statistical data analysis can be the basis for a judgment of risks. In addition, they can supply inputs for logical | + Link between "reality" and models 
+ The boundary conditions, under which the data was acquired, are often non-uniform and not known anymore at the time of analysis. 
- Extreme events do often not occur during the investigation period (incompleteness of data) |
<table>
<thead>
<tr>
<th>Methodology component</th>
<th>Description</th>
<th>Scope</th>
<th>Advantages / disadvantages</th>
</tr>
</thead>
</table>
| **Logical Trees: Fault tree analysis** | - FTA is used to determine logic functions of components or subsystems of a system, which can lead to an unwanted event (top event). In practice this includes the systematic identification of all possible failure combinations (causes) and the underlying basic events, which can lead to a given top event.  
- An FTA is a deductive method (downward logic). Starting point is a defined state of the analysed system (top event), which is continued top down to a basic event. For the quantitative determination of the frequency of the top event the reliability characteristics of the analysed basis events are needed. | trees (fault or event trees).  
- Statistical data analyses are an important basis of all quantitative analyses. | + FTA permits sharp quantitative statements.  
+ The graphical representation in a logical fault tree promotes the understanding for connections and links of a system, which are usually not easily recognisable.  
+ FTA also allows analysing events, for which no detailed data/information is available. Therefore data for particular components of the system is considered.  
- For large systems, the fault trees can strongly branch out and get very complicate.  
- On the component level the available statistical data is often insufficient too, hence the need for estimations with expert judgment.  
- The availability of statistical data and the multiplicity of relevant influence factors allow often only a comparative evaluation of variants. |
| **Logical Trees: Event Tree analysis** | - In the ETA events are determined, which can develop from a given initial event. It is an inductive analysis (initial event and subsequent events).  
- ETA illustrates possible events in (large) systems or plants, which can result after an initial event. Thus the consequences, which an initial event in a system causes, are pursued gradually up to a final state of the system (plant condition “function” or “loss”).  
- Each event in this chain has to carry the consequences of the preceding events. By using a simple graphical representation the logical operational sequence points out which of the subsequent subsystems fail or function (binary logic). | ETA can be used for the description and quantification by events of all kinds.  
- It is used preferentially for the investigation of dysfunctions and incidents in technical systems.  
- Analysis of consequences of events  
- Determination of frequency of events  
- Identification of possible safety measures | + ETA allows sharp quantitative statements.  
+ ETA illustrates and structures the possible consequences of an event systematically.  
- For large systems the trees can become unclear.  
- Similar disadvantages and difficulties as FTA |
### Methodology Component

<table>
<thead>
<tr>
<th>Description</th>
<th>Scope</th>
<th>Advantages / Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Logical Trees: Cause consequence analysis</strong>&lt;br&gt;C C A</td>
<td>- The method of the CCA links the fault tree analysis FTA and the event tree analysis ETA.&lt;br&gt;- CCA is used for the determination of relevant event scenarios.&lt;br&gt;- Failures, which can lead to a critical event, are analysed by using FTA. Consequences are analysed by using ETA.&lt;br&gt;- → FTA and ETA</td>
<td>- CCA is used preferentially for the investigation of dysfunctions and incidents in technical systems.&lt;br&gt;- → FTA and ETA</td>
</tr>
<tr>
<td><strong>Spread and effects models</strong>&lt;br&gt;</td>
<td>- Quantitative determination of the consequences of events, consisting of several steps: Spread analysis, exposition analysis, and analysis of effects.&lt;br&gt;- By applying a spread analysis the spatial and temporal spreading of released substances in the environment is determined, considering the environmental characteristics and atmospheric conditions. Pollutant concentration and/or heat or pressure effects are determined.&lt;br&gt;- The exposition analysis examines, which objects or persons are endangered in a particular situation.&lt;br&gt;- With the analysis of effects, it is examined, what effects toxicity, heat or pressure can have on the endangered objects and/or persons.&lt;br&gt;- The resulting consequences, which can be caused by a release of dangerous substances and/or by a release of energy, depend on property and quantity of the substance, the kind of release, spreading behaviour and the dose effect relations with radioactive or toxic materials or fire or explosion behaviour. The procedure is therefore only suitable if properties and effects on persons or objects of the materials involved are known.</td>
<td>- For detailed analyses, e.g. for systems/plants with a high danger potential (chemical industry) and/or in sensitive environment.&lt;br&gt;- For analyses with known environmental situation and clearly defined materials etc.</td>
</tr>
</tbody>
</table>
### Methodology component

#### Simulations
- An activity (process) is modelled and simulated several times. The model contains in particular all safety-relevant elements, which can fail with a certain frequency.
- Dynamic simulation models can consider temporal dependence and also the interaction of several subsystems.
- The influence of specific safety precautions on the overall system can be examined by changing a certain element in the system (change of components, etc.).

#### Scope
- Simulation of dynamic systems (change of different initial situations)
- Simulation of activities: For example repeated driving on road with different possible events.

#### Advantages / disadvantages
+ Statements to an overall system possible.
+ Image of reality in a model.
+ Possibility of analysing effects of interferences in the system.
- Can become very laborious. Specific computer programs needed.
- The behaviour of the elements of the system has to be known.

### SELECTION OF METHODOLOGY COMPONENTS FOR RISK EVALUATION

<table>
<thead>
<tr>
<th>Methodology component</th>
<th>Description</th>
<th>Scope</th>
<th>Advantages / disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert judgment</td>
<td>- Expert judgment is an estimation of several experts from the field of activity concerned to a particular question. The estimation reflects the knowledge and the experience of these specialists. - Expert judgment can be applied qualitatively and quantitatively.</td>
<td>- Expert estimations as an instrument for risk evaluation are applicable for all kinds of analysis. - Suitable for a first rough evaluation of complex questions as well as for the evaluation of routine questions</td>
<td>+ Low effort - The &quot;quality&quot; of estimation depends on the experience and knowledge of the experts - Expert judgments can be strongly affected by (current, individual) experiences - Danger of ignoring certain aspects (&quot;it cannot be, what may not be.&quot;) - Comprehensibility, transparency and comparability of different analyses are not given. - Acceptance of expert judgments for complex systems is questionable. - No explicit statements on remaining risks.</td>
</tr>
<tr>
<td>Best Practice, Standards</td>
<td>- The risk evaluation is done by demonstrating that the examined system corresponds to standards. - The risk evaluation is not done according to the extent of the risk, but at the presence of certain measures or at reaching certain characteristics (e.g. a certain pollutant concentration). - The procedure is closely coupled with planning of safety measures.</td>
<td>- Evaluation of questions for subject areas, where a more or less defined state of the art exists</td>
<td>+ Low effort, if the state of the art is clearly defined - Simple and comprehensible approach - Proceeding corresponds to the tradition and/or the habits - Proceeding does not take into account the extent of the risks (and/or the significance of the problem) - No explicit statements on</td>
</tr>
<tr>
<td>Methodology component</td>
<td>Description</td>
<td>Scope</td>
<td>Advantages / disadvantages</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------</td>
<td>-------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td><strong>Comparison of frequency or consequences (limit value)</strong></td>
<td>- The evaluation is made by comparison of the new system (the one to be examined) with an existing system (reference system).</td>
<td>- Comparisons within a defined subject area or within comparable subject areas.</td>
<td>+ The evaluation on the basis of comparisons is normally simple to understand and to communicate.</td>
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<tr>
<td></td>
<td>- The comparison is made by the individual risk $r$ of an affected person. The individual risk considers all scenarios and their effect on the regarded person, arising in the system.</td>
<td></td>
<td>- The frequency and/or the consequence is only one partial aspect of the risk (incomplete statement).</td>
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<td></td>
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<td>- Comparability of different systems with vastly different scenarios is not given.</td>
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<td></td>
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<td></td>
<td>- A statement on the overall system is not possible, because only separated aspects are evaluated.</td>
</tr>
<tr>
<td><strong>Comparison of individual risks (limit value)</strong></td>
<td>- The evaluation is made by a comparison of the new system (the one to be examined) with an existing system (reference system).</td>
<td>- Suitable for a quantitative risk assessment: e.g. industrial safety, practice of certain activities (also in traffic).</td>
<td>+ The evaluation on the basis of comparisons is normally simple to understand and to communicate.</td>
</tr>
<tr>
<td></td>
<td>- The comparison is made by the individual risk $r$ of an affected person. The individual risk considers all scenarios and their effect on the regarded person, arising in the system.</td>
<td>- Applicable, if reference values exist or can be appraised.</td>
<td>+ The individual risk covers all the dangers arising from the system considered and affecting an individual person. It provides in a comprehensive picture of the endangerment.</td>
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<td></td>
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<td>- Usually applied, if individual (few) persons are exposed to high dangers.</td>
<td>+ Comparisons of different subject areas are possible</td>
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<td>- The assumption that existing individual risks are acceptable does not necessarily have to be correct.</td>
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<td>- Suitability of safety measures is not assured.</td>
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<tr>
<td>Methodology component</td>
<td>Description</td>
<td>Scope</td>
<td>Advantages / disadvantages</td>
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</tbody>
</table>
| **Comparison of societal risks (limit value)** | - The evaluation is made by a comparison of the new system (the one to be examined) with an existing system (reference system).  
- The comparison is made on the level of the societal risk $R_o$. The determined societal risks of a system are compared with those of a reference system. | - Suitable for a quantitative risk assessment for clearly comparable systems: e.g. route choice for a transport from A to B. | + The evaluation on the basis of comparisons is normally simple to understand and to communicate.  
+ With the societal risk the overall system (all scenarios) is considered and a complete picture of the endangerment is provided.  
- Comparability of different systems is not given, because the size of the system (e.g. route distance) and characteristics directly affect the societal risk.  
- Suitability of safety measures is not assured. |
| **FN curve with acceptability line or areas** | - The representation of societal risks in the FN diagram shows, for which frequency a certain consequence level for a given system is reached or exceeded.  
- By defining an acceptability line in the FN diagram, the limit value of the accepted societal risk is also fixed. | - Risk management for transport and storage of dangerous goods (e.g.: Ordinance on Major Accidents in Switzerland)  
- Evaluation of chemical danger potentials  
- Evaluation of societal risks. | + The evaluation by means of an FN diagram is normally more or less simple to understand and to communicate.  
+ The suitability of safety measures can be considered (acceptance areas)  
- The evaluation is independent of the size of the regarded system, i.e. large systems are a priori at a disadvantage.  
- The comparison of different systems is difficult (definition of the acceptance line).  
- Linear systems (for e.g. traffic routes) must be divided into suitable sections for the assessment. The choice of a reasonable size of the sections represents a standardisation problem. |
**Methodology component** | **Description** | **Scope** | **Advantages / disadvantages**
--- | --- | --- | ---
**Cost-effectiveness (marginal costs)** | - The societal risk of a technical system can (usually) be lowered by additional safety measures, the more safety measures are proposed, the larger the expenditures (costs) are. It must be presupposed, that all conceivable measures and measure combinations are considered in each case.  
- Each measure or combination of measures is characterised by a certain reduction of the societal risk and by certain costs. It can be represented as a point in a risk-cost-diagram.  
- The lower envelope of the points in the risk-cost-diagram forms the optimal risk reduction strategy: Measures close to this curve represent the "optimal" risk reduction for a given cost level. Each technical system can be characterised therefore also by its characteristic risk reduction curve in the risk-cost-diagram.  
- The principle of the cost-effectiveness states, that the societal risks of a system can be mitigated up to that point on the risk reduction curve, where a certain cost-effectiveness of the safety measures is reached. | - Suitable for system-based approaches, where maximum safety is sought after and funds for additional safety measures are limited. | + Consideration of system size, making a comparison of different systems possible  
+ Consideration of an optimal allocation of funds  
+ Suitability of safety measures is explicitly assured.  
+ Maximum safety assured in the examined system with available (limited) funds.  
- Requires knowledge of possible safety measures, their costs and effectiveness.  
- Safety level is indirectly defined with the suitability of additional measures.  
- No explicit limits for the individual and the societal risk.

## SELECTION OF METHODOLOGY COMPONENTS FOR PLANNING OF SAFETY MEASURES

| Methodology component | Description | Scope | Advantages / disadvantages |
| --- | --- | --- | ---
| Expert judgment | - Expert judgment is an estimation of several experts from the field of activity concerned to a particular question. The estimation reflects the knowledge and the experience of these specialists.  
- Expert judgment can be applied qualitatively and quantitatively.  
- Experts evaluate measures or prioritise them. Their experience as well as all further available information forms the basis of this methodology component. | - Expert estimations as an instrument for the evaluation of safety measures are applicable for all kinds of analysis.  
- Suitable for a first rough evaluation of complex questions as well as for the evaluation of routine questions | → Methodology components for risk evaluation: Expert judgment  
- Comprehensibility, transparency and comparability of the arrangement/the suggestion of different safety measures are not ensured.  
- No explicit statements on the effectiveness of safety measures and on the remaining risks. |
<table>
<thead>
<tr>
<th>Methodology component</th>
<th>Description</th>
<th>Scope</th>
<th>Advantages / disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best practice, standards</td>
<td>- The risk evaluation is done by demonstrating that the examined system corresponds to standards.</td>
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<tr>
<td></td>
<td>→ Methodology components for risk evaluation: Best practice, standards</td>
<td>- Evaluation of safety measures for subject areas, where a more or less defined state of the art exists</td>
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<tr>
<td></td>
<td></td>
<td>- No explicit statements on the effectiveness of safety measures and on the remaining risks.</td>
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<td></td>
<td></td>
<td>- The suitability of safety measures is not considered.</td>
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<tr>
<td>Effectiveness concerning frequencies or consequences</td>
<td>- The evaluation of safety measures is done by means of effectiveness considerations.</td>
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</tr>
<tr>
<td></td>
<td>- Evaluation of safety measures in terms of their effectiveness concerning frequencies and/or consequences</td>
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<tr>
<td></td>
<td>- Safety measures with a larger effectiveness are preferred.</td>
<td>- Everywhere applicable, where safety measures have an influence only on one of the two components of the risk (frequencies or consequences)</td>
<td></td>
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<tr>
<td></td>
<td>→ Methodology components for risk evaluation: Comparison of frequencies or consequences</td>
<td></td>
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<tr>
<td>Effectiveness concerning individual risks</td>
<td>- The evaluation of safety measures is done by means of effectiveness considerations.</td>
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<tr>
<td></td>
<td>- Safety measures are evaluated particularly in terms of their effectiveness concerning the individual risk $r$ of an affected person. The individual risk considers all scenarios arising in the system and their effect on the regarded person.</td>
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<tr>
<td></td>
<td>- Safety measures with a larger effectiveness are preferred.</td>
<td>→ Methodology components for risk evaluation: Comparison of individual risks (limit value)</td>
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<tr>
<td></td>
<td>→ Methodology components for risk evaluation: Comparison of individual risks (limit value)</td>
<td></td>
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<tr>
<td></td>
<td>- With pure effectiveness considerations concerning individual risks, the suitability of additional safety measures is not considered.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effectiveness concerning societal risks</td>
<td>- The evaluation of safety measures is done by means of effectiveness considerations.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>- Safety measures are evaluated particularly in terms of their effectiveness concerning the societal risk of a system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Safety measures with a larger effectiveness are preferred.</td>
<td>→ Methodology components for risk evaluation: Comparison of societal risks (limit value)</td>
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<td></td>
<td>→ Methodology components for risk evaluation: Comparison of societal risks (limit value)</td>
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</tr>
<tr>
<td></td>
<td>- With pure effectiveness considerations concerning societal risks, the suitability of additional safety measures is not considered.</td>
<td></td>
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<tr>
<td>Effectiveness FN curve</td>
<td>- The representation of societal risks in the FN diagram shows, for which frequency a certain consequence level of a given system is reached or exceeded. The evaluation of the risks takes place by comparing with a fixed acceptance line (or acceptance ranges).</td>
<td></td>
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<tr>
<td></td>
<td>- The evaluation of safety measures is done by considering their effectiveness.</td>
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<tr>
<td></td>
<td>- Safety measures are evaluated particularly in terms of their effectiveness concerning the position of the curve in the FN diagram.</td>
<td>→ Methodology components for risk evaluation: FN curve with acceptability line or areas</td>
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<tr>
<td></td>
<td>→ Methodology components for risk evaluation: FN curve with acceptability line or areas</td>
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<tr>
<td></td>
<td>- With pure effectiveness considerations concerning frequency and consequences the suitability of additional safety measures is not considered.</td>
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</table>
## Methodology Components for Risk Evaluation: Cost-effectiveness (Marginal Costs)

<table>
<thead>
<tr>
<th>Methodology Component</th>
<th>Description</th>
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</thead>
</table>
| **Cost-effectiveness-analysis** | - The evaluation of additional safety measures is done by considering effectiveness and costs.  
- The effectiveness of a safety measure is compared with the related costs. The evaluation of the safety measure is done by considering the cost-effectiveness-ratio.  
- Safety measures with a small cost-effectiveness-ratio are preferred.  
- With the principle of the cost effectiveness relationship, the effectiveness of safety measures can in principle be considered for individual, societal or perceived risks. Application is common in connection with societal and perceived risks. |

<table>
<thead>
<tr>
<th>Scope</th>
<th>Advantages / disadvantages</th>
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</thead>
<tbody>
<tr>
<td>&quot;Methodology components for risk evaluation: Cost-effectiveness (marginal costs)&quot;</td>
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</table>

| **Cost-effectiveness-diagram** | - The societal risk of a technical system can (usually) be lowered by additional safety measures. The more measures are proposed, the larger the expenditures (costs) are.  
- Each safety measure or combination of measures is characterised by a certain reduction of the societal risk and by certain costs. It can be represented as a point on the risk cost diagram.  
- The principle of the cost-effectiveness states that the societal risks of a system can be mitigated up to the point on the risk reduction curve, where a certain cost-effectiveness of the safety measures is reached. For this limit value of cost-effectiveness, the term "marginal costs" is used. |

<table>
<thead>
<tr>
<th>Scope</th>
<th>Advantages / disadvantages</th>
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</thead>
<tbody>
<tr>
<td>&quot;Suitable for system-based approaches, where maximum safety is sought after and funds for additional safety measures are limited. &quot;</td>
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</tbody>
</table>

| "Methodology components for risk evaluation: Cost-effectiveness (marginal costs)" |
### General Introduction

<table>
<thead>
<tr>
<th>Type of risk assessment method</th>
<th>COUNTRY</th>
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<tbody>
<tr>
<td>Objective</td>
<td></td>
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<tr>
<td>Type of accidents</td>
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</tbody>
</table>

### 1. Methodology

1.1 Structure

1.2 Hazard Identification

1.3 Frequency calculation

1.4 Consequence assessment

1.5 Risk calculation

### 2. Risk Evaluation

2.1 Risk standards / Risk acceptability

2.2 Risk – based decision making
### 3. Experience in Practical Application

<table>
<thead>
<tr>
<th>3.1 Range and limitations of application</th>
</tr>
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<tbody>
<tr>
<td>3.2 Availability of input data</td>
</tr>
<tr>
<td>3.3 Specific advantages / disadvantages</td>
</tr>
<tr>
<td>3.4 Commercial availability of risk model</td>
</tr>
<tr>
<td>3.5 Time expenditure</td>
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<tr>
<td>3.6 Recommended improvements</td>
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</tbody>
</table>

### 4. Suitability of Method to Meet Specific Requirements of EU-Directive

In annex 1 the EU-Directive requires risk assessment for the evaluation of the following parameter; can the method be applied for this purpose?

<table>
<thead>
<tr>
<th>4.1 Annex 1– Chapter 1.1.3</th>
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<tbody>
<tr>
<td>Assessment of influence of specific characteristic of relevant parameters</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>4.2 Annex 1– Chapter 1.2.1</th>
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<tbody>
<tr>
<td>Assessment of discrepancies to minimum safety requirements</td>
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</table>

<table>
<thead>
<tr>
<th>4.3 Annex 1– Chapter 1.3.2</th>
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<tbody>
<tr>
<td>Assessment of influence of number of heavy goods vehicles</td>
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</table>

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<thead>
<tr>
<th>4.4 Annex 1– Chapter 2.2.3</th>
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<tbody>
<tr>
<td>Assessment of influence of high gradient</td>
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<tr>
<td>4.5 Annex 1– Chapter 2.2.4</td>
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<td>----------------------------</td>
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<tr>
<td>4.6 Annex 1– Chapter 2.6.2</td>
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<td>4.7 Annex 1– Chapter 2.9.3</td>
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<td>4.8 Annex 1– chapter 3.4</td>
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<td>4.9 Annex 1– chapter 3.7</td>
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5. Recommendations and Outlook

<table>
<thead>
<tr>
<th>5.1 Experience – based recommendations</th>
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<tr>
<td>5.2 Envisaged developments</td>
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