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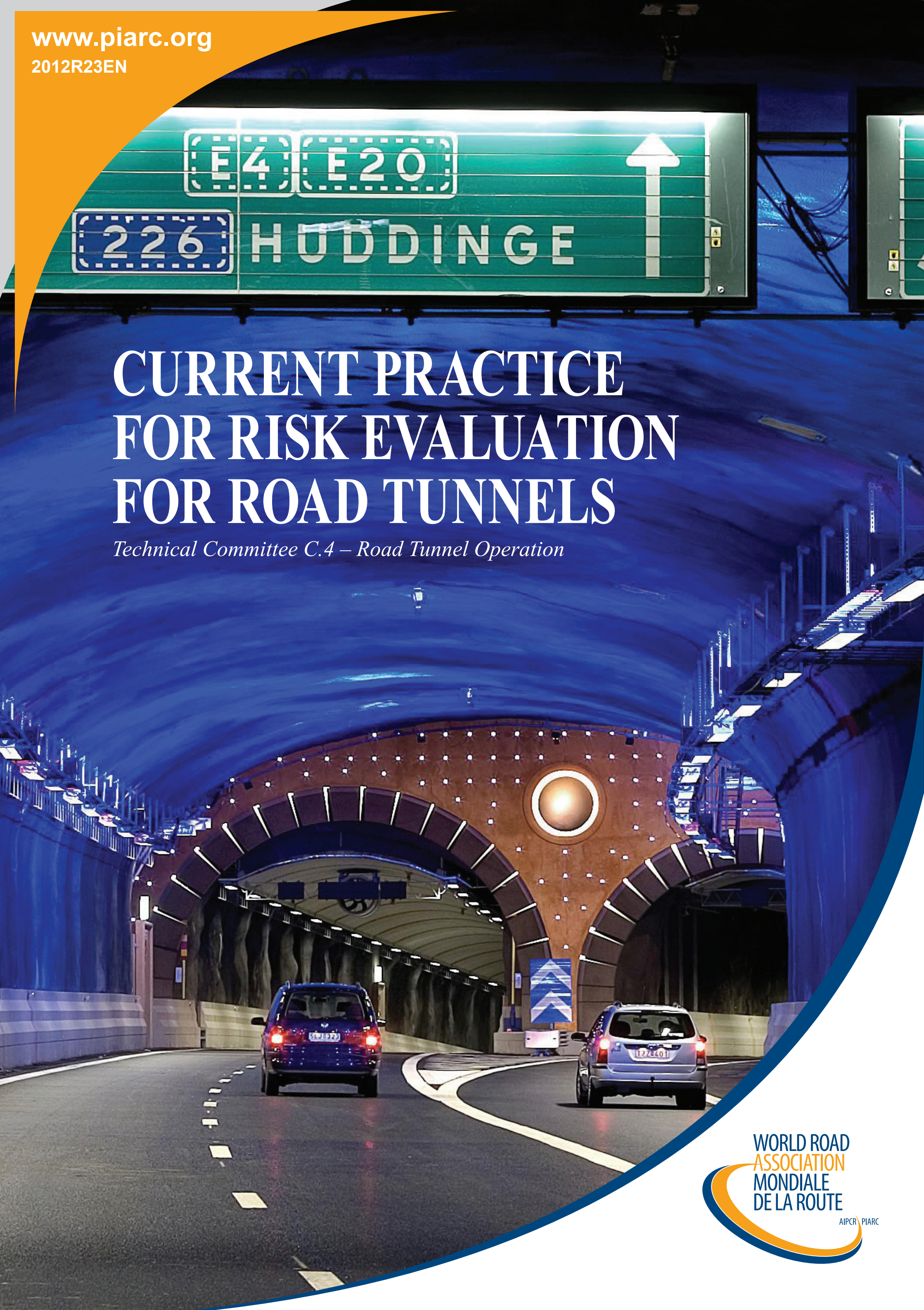
CURRENT PRACTICE FOR RISK EVALUATION FOR ROAD TUNNELS

Technical Committee C.4 – Road Tunnel Operation



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STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2008 – 2011 approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organizations or agencies.

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CONTENTS

SUMMARY

Risk evaluation is a fundamental part of the risk assessment process. It is the procedure by which consideration is given to the tolerability of risk, usually by measuring the calculated risk against pre-defined risk acceptance criteria. The definition of these criteria is not universal but is embedded in a specific legal, social and cultural environment and is influenced by many aspects. Although there are no universally accepted risk criteria for road tunnels, there are established criteria in use in some countries for certain applications.

Risk evaluation can take many forms, including qualitative approaches such as the evaluation of the outcome of risk scoring systems and the evaluation following implementation of prescriptive design guidelines; and quantitative approaches where risk analysis has been used to derive risk in terms of expected values or FN curves. Evaluation of quantitative approaches forms the main focus of this report, particularly for societal risk, where the principles are described with reference to practical approaches used in a number of different countries.

This report should be read in conjunction with the previous report of this Working Group, *"Risk Analysis for Road Tunnels"* [1]. For completeness, some key elements of the previous work are also included in the present report, including an update of the survey of practical methods of risk analysis, given in Appendices.

Societal risk for a particular tunnel may be evaluated against absolute or relative criteria; or both as is often the case in practice. Evaluation against absolute criteria requires an agreed threshold or target risk to be established for the project. The calculated risk for the tunnel must then fall below this target to be acceptable. Evaluation against relative criteria typically requires the establishment of a reference risk profile that represents an equivalent tunnel that is deemed to have an acceptable level of risk, typically because it complies with all the relevant standards and guidelines. The calculated risk for the tunnel must then fall sufficiently below that of the reference tunnel to be acceptable.

For risk expressed as the expected value (EV, the risk in terms of expected annual fatalities), the evaluation is fairly straightforward, although the definition of the threshold value, if not nationally accepted, will need careful consideration in the context of the specific project and achieve the buy-in from all the relevant stakeholders. This approach is easy to apply but does not take into account the distribution of consequences (accidents with very low probability/very high consequences only contribute to a minor extent to the expected value). If appropriate, a risk aversion factor may be included to offset this so that incidents with high numbers of fatalities are made less acceptable than the more frequent incidents with fewer fatalities.

For risk expressed in the form of an FN curve, graphical information is provided about the frequency of incidents and the distribution of the numbers of fatalities in those incidents. In some countries, absolute evaluation criteria are defined in the form of acceptance lines on the FN diagram and these reference lines are typically strictly linked to a specific analysis method or risk model. Acceptance lines in the FN diagram often have upper and lower limits between which an ALARP zone is defined, where risks should be reduced to as low as reasonably practicable. Risks in this zone should typically be reduced as long as the cost of the risk reduction is not disproportionate to the monetary benefit.

As with the absolute criteria for risk in terms of EV, the definition of the acceptability curves/boundaries in the FN diagram is not straightforward and is often a long-term process in which all stakeholders are involved. The comparative approach with FN curves is very useful for the risk-based comparison of alternatives but FN graphs can be difficult to interpret and need to be read very carefully, particularly where curves intersect.

To increase the robustness of risk evaluation, the different risk evaluation strategies described are often combined with each other and with other approaches such as scenario analysis where specific scenarios are investigated (modelled) to help optimise the level of safety provision to meet risk criteria such as limits for evacuation time or specific objectives for smoke management; and cost-effectiveness analysis where safety measures may be prioritised to ensure that the resources are spent in such a way that the maximum risk reduction is obtained.

Based on the information presented in this report, it is recommended that risk analysis and evaluation form just one of a number of bases for decision-making in tunnel safety management and that when determining risk evaluation criteria it is understood that the strategy for risk evaluation is strongly dependent on the method of risk analysis chosen and the specific scope and circumstances of the risk assessment. Although risk models try to be as close to reality as possible and try to implement realistic base data, it is important to consider that the models can never predict real events and that there is a degree of uncertainty and fuzziness in the results. Considering this uncertainty, the results of quantitative risk analysis should be considered accurate only to an order of magnitude and should be supported by sensitivity studies or similar. Risk evaluation by relative comparison (e.g. of an existing state to a reference state of a tunnel) may improve the robustness of conclusions drawn but care should be taken in the definition of the reference tunnel. Finally, the interpretation of the results of risk analyses requires sufficient experience and understanding of the methods and the evaluation strategies used.

From a legal point of view it can be stated that a systematic approach like risk evaluation on the basis of a systematic, well prepared risk analysis well serves the decision making process as a defence for subsequent legal investigation into a decision maker, their advisors and their decisions.

INTRODUCTION

The application of risk-based approaches in the process of tunnel safety management has gained greater importance as a basis for decision-making regarding tunnel safety. Risk-based approaches allow for a structured, harmonised and transparent assessment of risks for an individual tunnel. Risk evaluation is one of the most important yet sensitive elements of the overall risk assessment process that is illustrated in *figure 1, page 14*. This element is intended to answer the question of whether a tunnel is safe enough, i.e. whether the risks that have been identified/quantified in the risk analysis are acceptable or whether additional safety measures are needed to fulfil the safety targets.

For this purpose some kind of risk criteria have to be defined which can be used as target values in the evaluation process; the definition of such criteria is a demanding task because it is embedded in a specific legal, political, social and cultural environment (which may be different in different countries) and is influenced by many aspects. There are no universally accepted risk criteria for road tunnels, although there are established criteria in some countries.

Scope and objectives of the report

This report is intended to provide discussion on the various established strategies for the evaluation of the results of a risk analysis which represent the state of the art for the risk assessment of road tunnels. The most common approaches are presented and their practical use is demonstrated.

Furthermore, the most important factors are described which may influence the definition of quantitative or qualitative risk criteria. Practically used risk criteria are shown in the context of their typical applications.

Advantages and deficiencies of various approaches are discussed and recommendations are given in order to assist the reader to establish the best available approach for a specific problem. The report takes up the results of the report Risk Analysis for Road Tunnels (PIARC report N° ISBN: 2-84060-202-4) which was produced by the same working group in 2007. Hence the present report is closely linked to this previous report and follows the same methodical principles. Some key elements of the previous work are also included in the present report where needed to give a complete view of the risk assessment process. The present report includes in Appendices an updated version of the survey of practical methods of risk analysis – updated from the version in the previous report to account for latest developments.

Target audience

This document addresses a target audience at two different levels:

- on the one hand it is intended for tunnel engineers and tunnel managers in general who, even if they are not specialists in this field, can grasp the philosophy and the benefits of risk analysis for road tunnel safety in general and of risk evaluation in particular. Furthermore they can appreciate the range of practical methods available and their possible applications;
- on the other hand it is aimed at risk analysts, who can find in the document both a detailed explanation of different risk evaluation principles as well as a demonstration and discussion of their practical application for typical situations. The report may therefore support the selection of a suitable approach for the investigation of a specific problem.

Procedure

For the development of this report, the working group has met twice a year and has drawn on the experiences in the countries of its members through the following working process:

- review of the background of risk evaluation and identification of the principles in the context of road tunnel safety;
- review and identification of practical approaches to risk evaluation for road tunnels, based on the experiences of working group members;
- collection of the experience of risk evaluation, in particular the evaluation practices associated with the risk analysis methods described in the previous report of this working group (updated and included in the Appendices of this report)

The descriptions of the background and the principles for risk evaluation (*chapters 2, page 16 and 3, page 19*) as well as the exhibition of practical approaches (*chapter 4, page 32*) have been prepared by engineers who are experienced in the application of these methods. However, no check of the scientific basis of the individual methods was performed during the preparation of the present report and consequently no guarantee can be given for the reliability of their results.

1. RISK ASSESSMENT FOR ROAD TUNNELS

1.1. A SHORT INTRODUCTION TO RISK ASSESSMENT

The operation of technical systems always induces associated risks. Technical failures, malfunction, failures in operation or misuse may cause different kinds of incidents (breakdowns, accidents, etc.) with adverse effects for safety of people, property, or environment. The development of a technical system is always combined with efforts to avoid or reduce these risks. In principle this can be achieved by two different approaches:

- by practical experience,
- by systematically investigating potential hazards and resulting threats in advance, trying to eliminate their causes and / or reduce their consequences.

In the past in many countries the safety design of road tunnels to a great extent was based upon regulations and guidelines: if the applicable prescriptions of relevant guidelines were fulfilled the tunnel was regarded as safe. These guidelines had been developed over decades and were mainly based on the experience of everyday operation, including incidents and accidents.

However, this prescriptive approach has some shortcomings which are particularly evident in accidents exceeding the range of existing operational experience:

- even if a tunnel fulfils all regulative requirements it has a residual risk which is not obvious and not specifically addressed;
- a prescriptive approach defines a certain standard of tunnel equipment etc. but is not suited to take the specific conditions of an individual tunnel into account. Furthermore, in a major accident the situation is completely different to normal operation and a great range of different situations exceeding existing operational experience may occur.

Hence, in addition to the prescriptive approach, especially for complex systems a supplement is needed which specifically addresses emergency situations: a risk-based approach. Risk-based approaches allow a structured, harmonised and transparent assessment of risks for an individual tunnel, including the consideration of local conditions in terms of relevant influence factors, their interrelations and possible consequences of incidents. Moreover, risk-based approaches make it possible to propose relevant additional safety measures for the purpose of risk mitigation and can be the basis for decision-making considering cost-effectiveness in order to assure the optimum use of limited financial resources.

However, a risk-based approach cannot replace technical design specifications. For example, the results of a risk analysis can help to define functional requirements for a ventilation system of a tunnel, but to guarantee an adequate performance of the ventilation a set of technical parameters has to be defined which for example can be done in a technical design guideline; hence the prescriptive approach and the performance based approach are indispensable supplementary elements of a state of the art for safety planning of a road tunnel. Consequently, new international (such as the EC Directive 2004/54/EC, [2]) and national tunnel regulations are addressing risk assessment to an increasing extent.

In a risk-based approach, emergencies are systematically analysed, typically by applying scenario techniques; both the probabilities of scenarios as well as their consequences are addressed. A quantification of risks can be achieved by combining probability and consequences of each scenario. By summarising the partial risks of all scenarios the overall risk of a tunnel can be calculated. This approach also includes scenarios which may not yet have happened (and consequently are not covered by experience) but which may happen and may have major consequences. However, not all effects can be quantified and a risk analysis may also focus on specific questions or specific scenarios without investigating the complete range of possible accidents. Therefore different methods have been developed and are practically applied (see *chapter 1.3. page 14* and *appendices, page 64*) and the selection of the most suitable method to investigate given issues has to match the specific problem, the required depth of assessment and the available resources.

In a risk analysis different types of risk can be investigated:

- harm to a specific group of people (fatalities and/or injuries): the most common risk indicator is fatalities referring to the group of tunnel users; in specific situations it may also be necessary to address other groups of people possibly affected by the consequences of accidents, e.g. people living next to tunnel portals (in case of accidents with dangerous goods) or above the tunnel (in case of damage to the tunnel structure);
- loss of property/economical loss: typical examples are damage to the tunnel structure (resulting in repair costs) and longer periods of tunnel closure due to damage caused by an accident (resulting in loss of toll income /and/or higher transport costs as well as consequences for local, regional or national economy);
- damage to the environment: although tunnels normally limit the damage to environment the spill of dangerous fluids through the tunnel drainage system may cause environmental pollution if adequate protection measures are not in place;
- damage to immaterial values: e.g. damage to the reputation of a company, region or a country as a consequence of the reaction of media to an accident with major consequences; these indirect long-term effects tend to be underestimated; they are of considerable importance for risk evaluation (see *chapter 2, page 16*).

Furthermore, results of a risk analysis can be used as a basis for further investigations, such as evaluation of socio-economic consequences.

Risks can be addressed in a quantitative or in a qualitative way. Qualitative methods typically focus on the functional analysis of the sequence of events and the interaction of people, systems and procedures. With quantitative methods, characteristic risk values for the whole tunnel can be calculated (discussed in more detail in *chapter 1.3. page 14*).

If risks are quantified, this can be done for individuals or for specific groups of people. The individual risk is the risk to an individual person who uses a tunnel, or lives near the tunnel. It is not only determined by the hazards (which provoke the risk) but also by the exposure of the individual person to these hazards. The risk to a defined group of people is called societal risk. The societal risk to tunnel users/neighbours is the most common quantitative risk indicator for the risk assessment of road tunnels.

1.2. THE RISK ASSESSMENT PROCESS

Risk analysis is embedded in the risk assessment process which includes the following three elements:

- **risk analysis:** 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 (see the previous PIARC report *"Risk Analysis for Road Tunnels"* [1]);
- **risk evaluation:** Risk evaluation is directed towards the question of acceptability of the identified risks to answer the question *"Is the estimated risk acceptable?"* For a systematic and operable risk evaluation, risk criteria have to be defined and it has to be determined whether a given risk level is acceptable or not.
- **risk reduction:** If the estimated risk is considered as not acceptable, additional safety measures have to be proposed to reduce risk.

The procedure for a risk analysis can be divided into the following 4 steps:

- definition of the system;
- hazard identification: Systematic process to identify and structure all relevant hazards, and to analyse their correlating effects;
- probability analysis: Determination of the probabilities of relevant events/scenarios;
- consequence analysis: Investigation of consequences of relevant scenarios.

The simplified flowchart in *figure 1, following page,* illustrates the main steps of the risk assessment process.

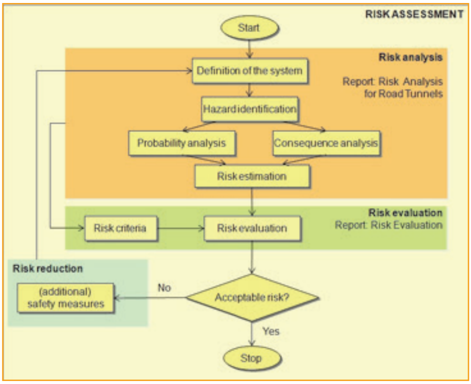

FIGURE 1 – FLOWCHART OF THE PROCEDURE FOR RISK ASSESSMENT [1]

1.3. CURRENT PRACTICE OF RISK ANALYSIS FOR ROAD TUNNELS

A broad spectrum of qualitative or quantitative methodological components exists for each step of the risk assessment process. For a risk analysis, different components are often combined to a more complex methodological approach. For example, in practical applications it is usually necessary to combine qualitative and quantitative components because of lack of data.

A complete procedure for risk assessment can be developed by combining the methods for risk analysis, risk evaluation and risk reduction. However, the different components are not arbitrarily combinable; rather certain evaluation methods need certain analysis components.

Risk-based approaches can be partitioned into the following two types:

- **scenario-based approach:** A set of relevant scenarios is defined, the probability of each scenario can be estimated and the possible resulting consequences are analysed (in some scenario-based approaches the estimation of the probabilities is not applied). The risk assessment is done separately for each single scenario on the basis of its characteristic indicators;
- **system-based approach:** By applying a system-based approach, risk values for an overall system are estimated. Thus all relevant events/scenarios which can affect persons in the system considered are taken into account. The risk assessment is done for the whole tunnel system investigated on the basis of the risk values of the system.

For each of the two different approaches an example is given in *figure 2, following page* and *figure 3, following page,* respectively.

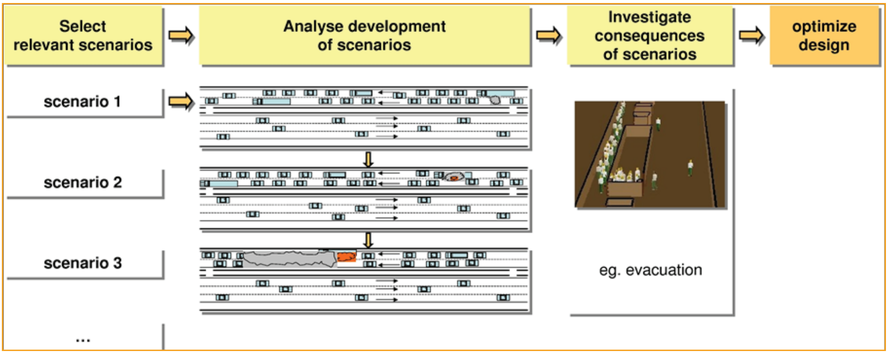

FIGURE 2 – RISK ANALYSIS – EXAMPLE OF SCENARIO-BASED APPROACH

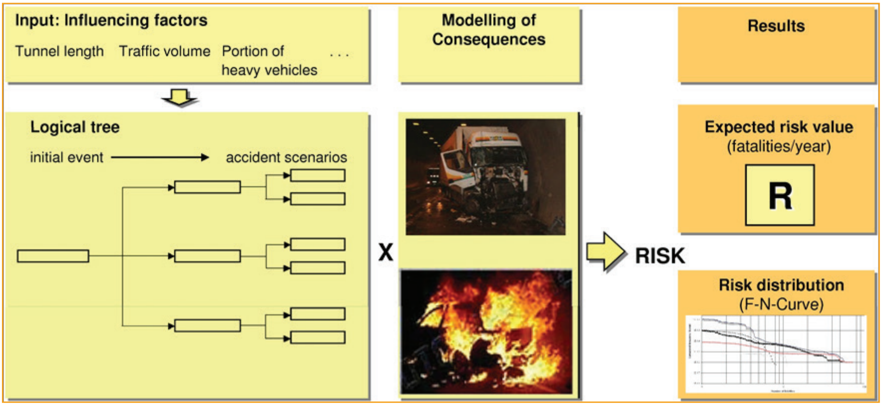

FIGURE 3 – RISK ANALYSIS – EXAMPLE OF SYSTEM-BASED APPROACH

In the PIARC Report *"Risk Analysis for Road Tunnels"* [1] the following recommendations are given for the practical use of risk analysis:

- select the best method available for a specific problem;
- be aware that whatever method you choose, you are always using a model which is a more or less major simplification of the real conditions. The method can never predict the course of a real event but helps you to make decisions on a sound and comparable basis;
- whenever possible, use specific data for quantitative methods. If specific data are unavailable, at least check the origin of the data you intend to use (are the conditions relating to infrastructure, traffic, etc, similar to your situation?). Be aware that specific features may be included in risk models that are not valid for your tunnel;
- for these reasons, risk analysis should only be performed by experts with sufficient experience and understanding of the methods they use;
- be aware that the result of a quantitative risk analysis must be interpreted as an order of magnitude and not as precise number due to the influence of uncertainties;

- when selecting a method for a risk analysis, you should also consider how to evaluate the results since the method of risk analysis and the strategy of risk evaluation are not independent.

The PIARC Report *"Risk Analysis for Road Tunnels"* [1] also presents a description of several practical methods. This survey of practical methods was updated and is attached to this report in the Appendices.

One of the methods presented – the OECD/PIARC model DG-QRAM [3] – is specifically dedicated to the evaluation of the risk of transport of dangerous goods through road tunnels. Some other methods also include dangerous goods transport risks. However, in practice, the risk due to the transport of dangerous goods is often analysed and evaluated separately because of its particularities:

- the transport of dangerous goods is regulated by specific prescriptions (ADR, [4]);
- great diversity of different substances entails a great variety of possible accident scenarios;
- many scenarios are characterized by extremely low frequencies and very high possible consequences.

2. THE BACKGROUND TO RISK EVALUATION

2.1. RISK EVALUATION AS A BASIS FOR DECISION-MAKING

When a risk analysis is performed, it is important to realise that decision-making about risks is complex. Not only technical and mathematical aspects are important, but ethical, political, societal and other factors have an important role as well. Whereas risk analysis is a scientific process of assessment and/or quantification of probabilities and the expected consequences of identified risks, risk evaluation is a socio-political process in which judgments are made about the acceptability of those risks.

2.2. FACTORS INFLUENCING RISK PERCEPTION

The discussion about the acceptability of risks is strongly influenced by risk perception. It is important to know that human behaviour is primarily driven by perception and not by facts or by what is understood as facts by risk analysts and scientists [5], [6], [7]. Most cognitive psychologists believe that perceptions are formed by common sense reasoning, personal experience, social communication and cultural traditions. Perceptions of risk can therefore vary significantly between technical experts, decision-makers, stakeholders and others. For this reason, the need to effectively communicate the level of risk involved in an activity is essential if an informed, valid decision is to be made. Technical experts tend to emphasise factors in terms of the probability of an occurrence or its likelihood and consequences, while a layperson tends to emphasise factors such as the following [5], [8], [9], [10], [11], [12], [13] and [14]:

- **perceived Benefits:** It's easier for people to accept risks when the expected benefit is clear (nobody questions the use of cars although road traffic causes a risk that would never be accepted with other technical systems);
- **voluntariness:** People are more concerned about risks that are imposed (accident in chemical industry) rather than voluntarily accepted (mountain climbing);
- **controllability:** People are more concerned about risks not under personal control (flying in an aeroplane) than those under personal control (driving a car);
- **familiarity:** People are more concerned about unfamiliar risks than familiar risks;
- **understanding:** People are more concerned about poorly understood activities than those that may be understood;
- **natural / man-made:** People are more concerned about man-made risk than about natural risk;
- **scientific uncertainty:** People are more concerned about risks that are scientifically unknown or uncertain than risks well known to science;
- **reversibility:** Risks which have potentially irreversible adverse effects are perceived to be greater than risks constituting no long-term threats;
- **dreadfulness:** The worse (more suffering) the possible consequences from a risk, the more concerns are evoked;
- **catastrophic potential:** People are more concerned about fatalities and injuries that are grouped in time and space (e.g. aeroplane crashes) than about fatalities and injuries that are scattered or random in time and space (e.g. car accidents);
- **media attention:** Media attention is a key factor for the influence of risk perception on public opinion; fires in tunnels are reported widely in the international press for their nature, rareness and maybe the exceptional dimension of the impact. By contrast, information about road accidents with many more annual casualties is often reported only briefly, if at all.

Some of the above mentioned factors can be considered rationally and objectively (e.g. voluntariness), others are more the result of subjective awareness. Risk analysts, recognising the legitimacy and importance of public values, have begun to incorporate such factors into risk-based decision making in terms of specific concepts. The following section (2.3) will give a brief overview of the concept of risk cases, considering benefit, voluntariness and controllability of risk.

2.3. THE CONCEPT OF RISK CASES

From a risk management point of view, the implementation of the most relevant aspects of risk perception should be implemented in the risk assessment process. In engineering terms this means that the goal should be to consider a small number of factors affecting risk evaluation and take the most relevant of these into account in a systematic and operational way. A concept of risk cases was introduced in [15] (*figure 4*).

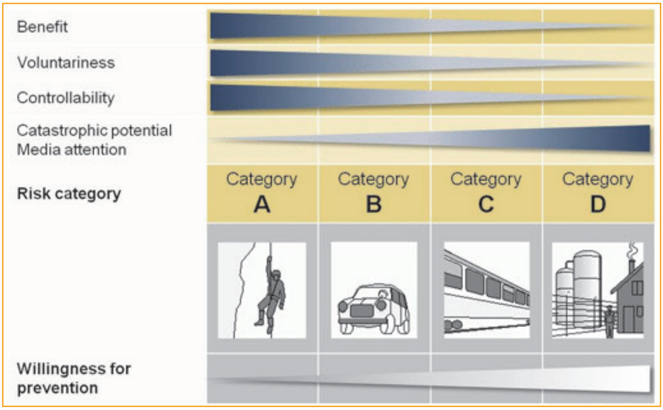

FIGURE 4 – CONCEPT OF RISK CASES (FOLLOWING MERZ [15])

The acceptance of risk in the four cases of the concept depends on the degree of the expected benefit, voluntariness and controllability of the activity. As these factors decrease, risk acceptance also decreases and the corresponding willingness for prevention increases:

- **case A:** Voluntary risk exposition in order to satisfy one's desires,
- **case B:** High degree of self-determination, direct individual benefit,
- **case C:** Low degree of self-determination, individual benefit,
- **Case D:** *"Involuntary"*, imposed risk exposition, no direct benefit.

For example, a mountaineer can be classified in case A. He is aware of the specific risk associated with this activity, is willing to accept a certain (high) level of risk and can influence this risk to a high degree. On the other hand, children living in the neighbourhood of a chemical plant have no way of knowing about or influencing the risks so would be classified in case D.

2.4. RISK AVERSION

The evaluation of risk is clearly influenced by risk perception; this effect is sometimes called risk aversion. Risk aversion refers to the fact that some accidents are perceived to be much worse than their inherent risk would indicate. For example an accident with a hundred fatalities and a frequency once every one hundred years may be judged much worse than a series of accidents, each with one fatality and a frequency of one per year, although the risk in terms of expected value is the same in both cases. It has to be noted that there is no generally accepted definition for the term risk aversion.

Depending on the field and/or scope, different definitions are used. Risk aversion can also depend on the activity considered (e.g. risk aversion for road tunnels is not the same as for nuclear plants) and all the other factors, which influence risk perception in general (*chapter 2.2, page 16*), may also influence risk aversion. Therefore, in accordance with the findings of risk perception and evaluation research, it has to be stated that risk aversion is more than a function of the extent of direct damage.

The (public) reaction to certain accidents strongly affects the actions of those responsible for a system (e.g. the authorities). A number of examples are known where the indirect effects of such large accidents have directly led to the collapse of companies or to the implementation of more stringent (and often costly) regulations.

Therefore the aspect of risk aversion is often included in strategies for risk evaluation by intentionally overvaluing the risk of accidents/scenarios causing large consequences in the risk evaluation process. Setting quantitative values for a risk aversion function is a subjective process and reflects also value judgement. It should be noted that including risk aversion or setting a risk aversion function is not an arbitrary process and depends on the activity considered.

3. PRINCIPLES FOR RISK EVALUATION

3.1. INTRODUCTION

The definition of criteria for risk evaluation takes account of risk perception in various forms, depending on the chosen methodological approach and consequence indicators. These indicators may be expressed as deterministic or non-deterministic. Different criteria for acceptability of risk may then be specified for each. Deterministic criteria may specify, for example, an acceptable evacuation time. Non-deterministic, risk-based criteria include an evaluation of both the frequency/probability and the resulting consequences of accidents. Establishing evaluation criteria can be done in different ways with different levels of complexity. From a practical point of view it should be noted that there are several approaches to the implementation of risk evaluation strategies. Some of the most relevant are summarised in the following sections. In practice, combinations of these strategies are often applied.

An important aspect of the risk assessment process is the discussion, and sometimes quantification, of uncertainty in the assessment of frequencies and consequences. This aspect also has to be taken into account in the evaluation of risk, especially for the application of absolute risk evaluation criteria. In practice, uncertainty is often investigated through sensitivity analyses or similar procedures associated with the risk analysis rather than by incorporating such aspects in the definition of risk evaluation criteria. These aspects of uncertainty are therefore not discussed in detail in the following sections of this report which are focussed on the different approaches to the implementation of risk evaluation strategies.

3.2. QUALITATIVE APPROACHES

There are a wide range of different approaches to qualitative risk evaluation. As mentioned in chapter 1 the most common approach is the application of prescriptive based criteria such as regulations, standards and guidelines. Other common approaches include the following:

- safety audits;
- checklists;
- points schemes – such as that applied to existing tunnels in Europe, under the aegis of the German Automobile Association, ADAC. A similar approach has been chosen for the EuroTAP program which gives a final qualitative *'point'* for each tunnel corresponding to *'very good'*, *'good'*, *'acceptable'*, *'poor'*, *'very poor'*;
- expert evaluation – e.g. judgement by a team of experts on the basis of scenario analyses.

All these approaches have in common that they are performed by individual experts or a group of experts. The results of such analyses where decisions are based on judgement should be supported by a coherent and conclusive explanation. A commonly used method to support the analysis, classification and evaluation of risks in a qualitative approach is the risk matrix (*figure 5, following page*).

In some cases, qualitative approaches may be used as a first step in the overall risk assessment process, to act as a screening tool whereby the lower risk elements are filtered out and attention for more detailed quantitative and/or deterministic analysis is focussed on the higher risk elements.

Points schemes and expert assessments are sometimes combined to give a qualitative approach whereby risk events are scored for their likelihood and probability. The combination (multiplication) of these scores may then be used to determine a risk value that can be used to classify risk on a numerical scale or a scale of tolerability. Such systems may be useful for the comparison of risks and the identification of risk events that warrant particular attention for a particular tunnel.

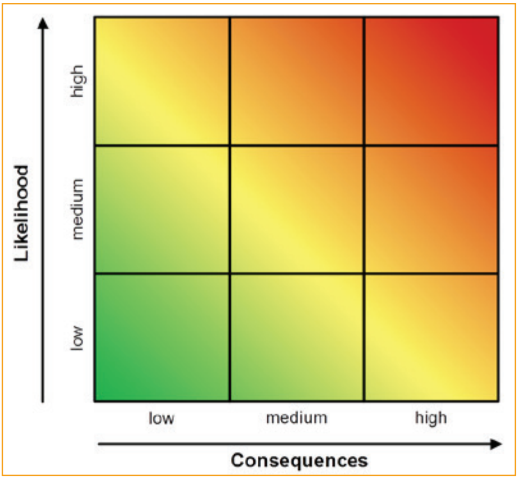

FIGURE 5 – EXAMPLE OF A RISK MATRIX

3.3. QUANTITATIVE EVALUATION OF SOCIETAL RISK

3.3.1. Definition of societal risk

Societal risk is defined by the Institution of Chemical Engineers [7] as *"the relationship between frequency and number of people suffering from a specified level of harm to a given population and a number from the realization of specified hazards"*. In other words it is the resulting risk to a group of people due to all hazards arising from an operation (*figure 6*). The level and nature of consequences is often measured in terms of loss of life (fatalities).

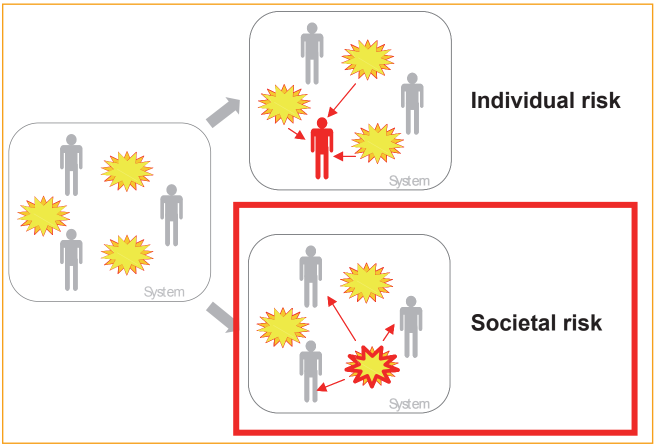

FIGURE 6 – SOCIETAL RISK

The analysis and evaluation of societal risk is typically with a system-based approach, resulting in the risk being expressed in terms of the (statistically) expected value.

3.3.2. Representation of societal risk

In practice the most common and suitable ways to express and to present societal risk are:

- FN diagram,
- Expected (risk) value (EV),
- Perceived risk (weighted expected value including risk aversion),
- Monetary risk.

The different approaches are discussed briefly in the following sections.

FN diagram

One of the most commonly used formats for representing risks is the so called Farmer diagram or FN diagram (*figure 7*). FN diagrams are frequency-consequence graphs – usually plotted on a double logarithmic scale – showing the cumulative frequencies (F) of incidents involving N or more units of damage. On the x-axis the consequences are given, usually in terms of fatalities, but in principle any other type of consequences could be considered. On the y-axis the frequency of occurrence of the corresponding incidents are given. It should be taken into account the cumulative type of consequences denoted by the expression of N or more units of damage (e.g. fatalities).

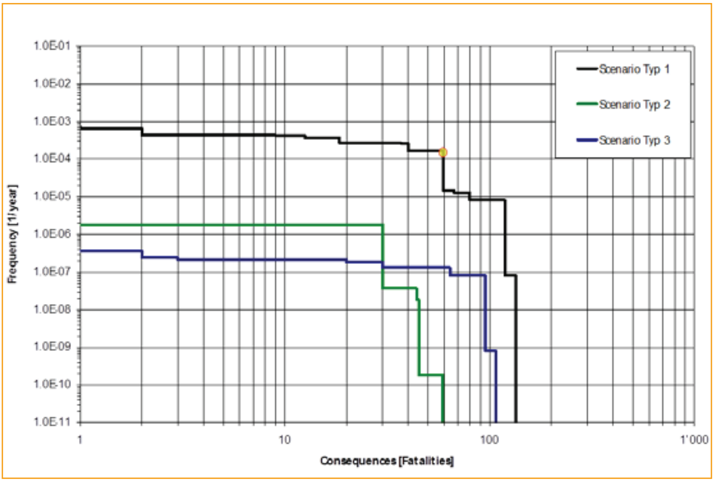

FIGURE 7 – FN DIAGRAM (FICTIOUS EXAMPLE)

In the example FN graph in *figure 7*, the yellow marked point on the black curve shows that, statistically, an incident with consequences of 60 or more fatalities has to be expected with a frequency of about 2 * 10^{-4} per year (every 5,000 years).

FN diagrams may be applied to illustrate the risk profile for a specific activity or for a specific type of hazard such as a fire in a road tunnel. FN diagrams provide information on the magnitude of consequences in relationship to the (cumulated) frequency of the type of hazard investigated (one line in the F-N diagram). Typically the units for the frequency correspond to 1 year and sometimes also a normalisation is included e.g. [1/km].

Expected value (EV)

A simple measure of societal risk is the EV. It is the long-term average number of statistically expected fatalities per year due to a particular hazard and for a particular system, e.g. a tunnel. For a particular incident, it is equal to the probability/frequency of the incident (pi), multiplied by the unit of consequences (Ci), e.g. the number of fatalities caused[1]. The fatality rates of all relevant scenarios (n) may be summed to give the total EV for the accident type or the system as a whole.

$$EV(=R_0) = \sum_{i=1}^{n} p_i * C_i = \int_0^{\infty} p(C) * Cdc \qquad (1)$$

Expressing risk in terms of the EV has the advantage of allowing the total risk of the tunnel system to be expressed as a single number. However, this may also be a drawback, as such a single number may conceal and obscure important aspects of the specific risk profile. This means that it treats all consequences/fatalities as equally important, irrespective of the number of lives that may be lost simultaneously in a major accident, unlike FN curves which illustrate the distribution of fatalities. The differentiation between high-frequency, low consequence accidents and low-frequency, high consequence accidents is not possible with the EV alone.

Perceived risk (weighted expected value including risk aversion)

The fact that some accidents are perceived to be much worse than their direct consequences would indicate is called risk aversion (*section 2.4, page 18*). Risk aversion can be implemented in the expected value calculation with weighting factors, in particular by considering a risk aversion factor φ as a function of the consequences (C_i):

[1] Formula (1) shows also the definition for the expected value if Ci has a continuous probability distribution; in the following the further definitions focus on discrete probability distributions for the sake of simplicity.

$$R_p = \sum_{i=1}^{n} p_i * C_i * \varphi(C_i) \qquad (2)$$

Figure 8 illustrates the effect of including risk aversion in a risk analysis. The following aversion factors were considered:

- f (= φ) = 1 for the accident consequence class 1 – 10 fatalities,
- f (= φ) =3 for the accident consequence class 10 – 50 fatalities,
- f (= φ) = 10 for the accident consequence class more than 50 fatalities.

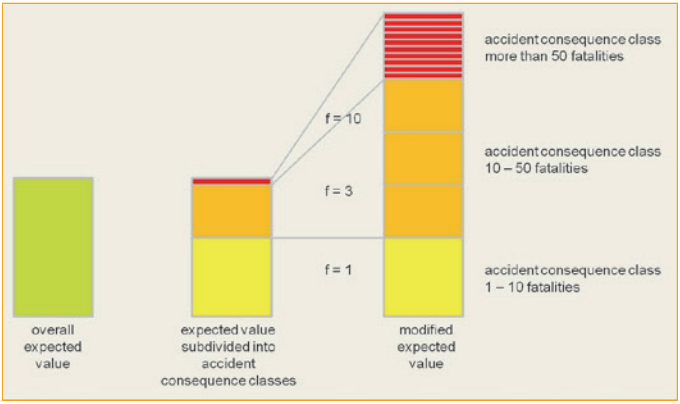

FIGURE 8 – EXAMPLE OF INCLUDING RISK AVERSION IN RISK ASSESSMENT

In current practice the resulting risk is called *"perceived (societal) risk"* [16]. *Figure 9* shows a selection of risk aversion functions φ (C_i) which have been used in risk analyses in different technical fields and shows the variety of aversion factors or functions used.

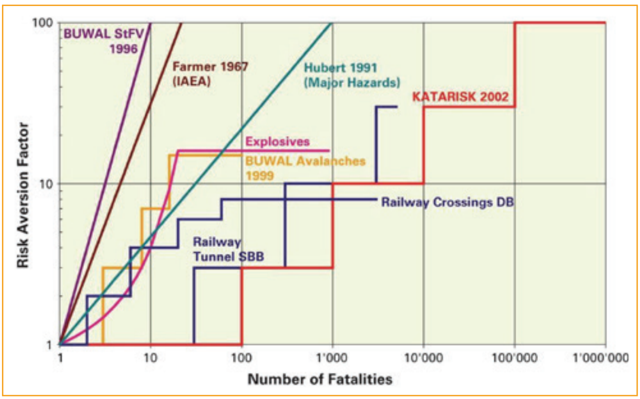

FIGURE 9 – RISK AVERSION FUNCTIONS USED IN OTHER STUDIES AND FOUND IN LITERATURE [17]

It has to be noted that each risk aversion function has been developed for a specific purpose and a specific field of application. Therefore it is not possible to define or choose one of these examples as suitable for risk analyses for road tunnels. *Figure 9* rather illustrates the variety of applied risk aversion functions.

Monetary risk

From a practical point of view, the determination of acceptability criteria can be based on the practicable principle of the optimal allocation of available resources. Therefore an optimisation between cost for additional risk reduction measures and the corresponding benefits has to be determined. It can be derived from a cost-effectiveness analysis [16]. As a result the monetary risk (R_m) has to be assessed, including the so called marginal costs (ϖ_i). Marginal costs are the price one is willing to pay for a marginal increase in safety or – in other words – the willingness-to-pay for saving one unit of damage. In the context of fatality risk it is the willingness-to-pay for saving a statistical life.

$$R_m = \sum_{i=1}^{n} p_i * C_i * \varphi(C_i) * \varpi_i \quad (3)$$

Example: If the marginal cost per life saved is fixed to 5 M€ and the calculated expected value R_0 for a certain type of scenario is 0.1 fatalities per year, the resulting monetary risk R_m is 0.5 M€ per year (excluding risk aversion for simplicity).

3.3.3. Evaluation of societal risk represented as EV

Application of absolute criteria

A widely used strategy for risk evaluation is based on the comparison of the resulting EV for a tunnel with a defined maximum threshold, defining the level of acceptable risk. As long as the assessed EV is lower or at an equal value to the defined threshold, the risk for the tunnel is evaluated as acceptable.

The application of absolute criteria is simple but the determination of thresholds as a basis for decision-making and the definition of what is an acceptable risk is not straightforward and has to be implemented very carefully. Definition of these criteria needs a commitment from all involved stakeholders, including the responsible legal authorities if the criteria are to be included in a legal basis.

Application of relative criteria

In contrast to the application of absolute criteria, the results of a risk analysis for a specific tunnel – expressed as EV – are compared to the EV resulting from the application of the same risk analysis methodology for a reference tunnel. The reference tunnel is normally a tunnel similar to the tunnel to be investigated but which complies with all requirements and fulfils all conditions defined in the guidelines etc. The assessed EV for the reference tunnel is used as a target value for the risk evaluation so that the expected risk value of the tunnel under assessment should be below or equal to this target value.

All relative risk evaluation strategies rely on the concept of a *"reference tunnel"*. In practice it is sometimes unclear exactly how to define this reference tunnel. This approach is a *"translation"* of the prescriptive approach into the concept of a performance-based risk assessment by quantifying the risk for a tunnel that fulfils the relevant regulations.

The result of the comparison of two singular values is clear and easy to interpret and communicate. However, there is some loss of information (e.g. compared to an FN curve); this is particularly relevant for incidents with very low probabilities and very high damage (e.g. typically accidents involving hazardous goods); such accidents may contribute little to the expected risk value. In contrast to the application of absolute criteria, the aspect of uncertainties in the assessment of frequencies and consequences is of minor importance due to the fact that the evaluation is based on a relative comparison.

3.3.4. Evaluation of societal risk represented by the FN curve

Application of absolute criteria

A typical representation of a practical application of acceptability criteria in the FN diagram is shown by the criterion lines in *figure 10, following page*. In the diagram a predefined acceptability curve has been determined. Resulting FN curves which are above the acceptability curve are evaluated as not acceptable, FN curves below as acceptable. Due to the characteristics of the used risk analysis methodology such absolute risk acceptance criteria are strongly related to the methodology which has been applied for the risk analysis.

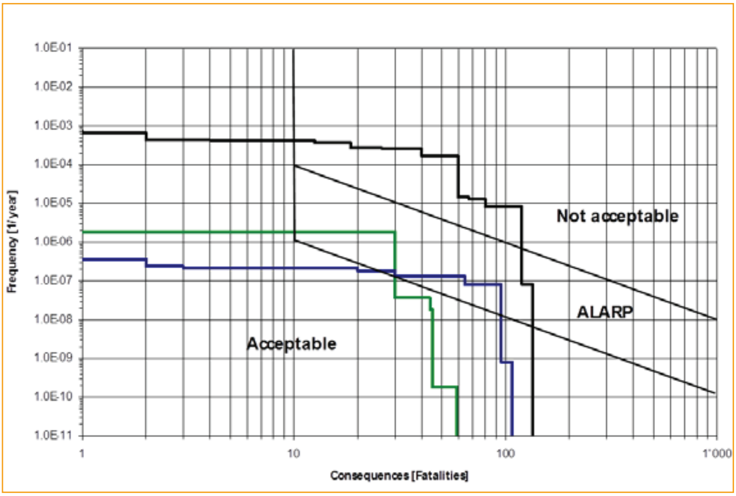

FIGURE 10 – FN DIAGRAMS INCLUDING CRITERIA OF ACCEPTABILITY (FICTIOUS EXAMPLE)

For practical applications, there are often two lines defined in the FN diagram. For the area that lies between the acceptable and unacceptable risk lines, in general the philosophy is to implement risk reduction measures on the basis of cost-effectiveness considerations. A commonly used principle for this is the ALARP principle where risks are to be reduced to As Low As Reasonably Practicable. It implies that risk reduction in this area should be implemented as long as the costs of risk reduction are not disproportional to their risk reduction effects. The definition of disproportionality may vary between schemes but this could mean that the risk reduction measure should be implemented if the value of the risk mitigation is of at least the same value as the resources required to implement it.

Risk aversion can be included in the acceptability criteria by changing the slope of the acceptability curve. The steeper the gradient of the curve, the less acceptable the incidents of greater consequences.

In practice there are many different acceptability lines which have been used in different projects and/or different situations. These curves vary considerably and only in a few countries are officially defined risk acceptance curves available (e.g. in Italy, the Netherlands and in Switzerland).

Application of relative criteria

Similarly to the relative criteria using the EV, the approach with FN curves also relies on the reference tunnel concept. The same risk analysis methodology as used for the tunnel under consideration is applied for the *"reference tunnel"*, resulting in a second FN curve. Evaluation is by relative comparison of the two curves where the curve of the *"real"* tunnel should be sufficiently below or close to the curve of the *"reference tunnel"* (*figure 11*).

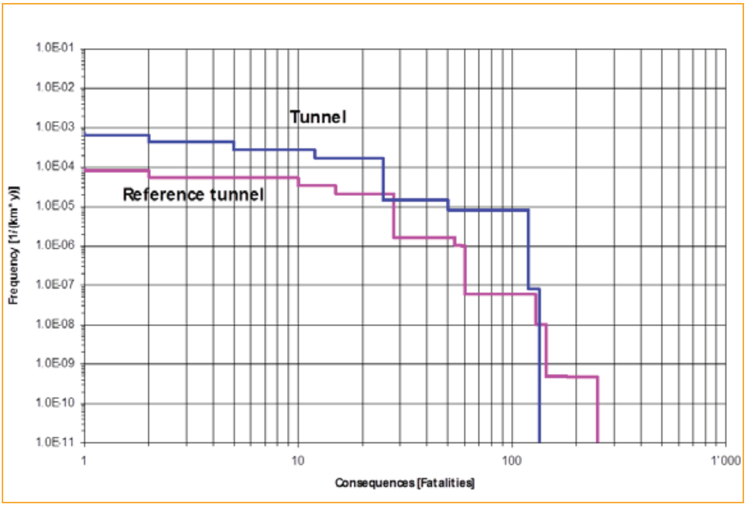

FIGURE 11 – COMPARISON OF FN CURVES (FICTIOUS EXAMPLE)

In practice it is often difficult to evaluate risks by comparing two FN curves, especially when they intersect. In such cases, the results of the comparison of two curves may be ambiguous and the interpretation may be difficult.

3.3.5. Cost-effectiveness

The cost-effectiveness approach is intended to ensure that the resources spent to reduce risk are spent in such a way that an optimised level of safety is obtained. Therefore the purpose of cost-effectiveness analyses is also to help to set priorities among different safety measures.

A cost-effectiveness analysis according to [16] contains the following steps:

- identification of all possible safety measures. This list must include all individual safety measures, as well as combinations thereof. The reason for this is that some combinations may be more effective than the sum of their individual effectiveness. Some might only be effective if others have been realised;
- assessment of the effectiveness and the cost of all safety measures and meaningful combinations. The effectiveness is measured as the reduction of the monetary risk (R_m). The cost includes the initial investment cost as well as the ensuing annual operating and maintenance cost. Both effectiveness and cost are expressed in monetary units (e.g. in million € per year);

- representation of all safety measures and meaningful combinations in a risk-cost diagram (*figure 12*). Each safety measure and combination is represented as a single point whose position is defined by the residual risk value and the associated cost;
- identification of the optimal risk reduction curve, defined by connecting all points which lead to the largest risk reduction at all cost levels. Safety measures which are not part of the optimal risk reduction curve are not optimal (or disproportional) in the sense that the same risk reduction could be achieved at lower cost;
- the optimal safety measure or combination in the sense of the marginal cost criterion is indicated by the point where the slope of the optimal risk reduction curve changes value larger than -1[2]. Safety measures which are located on the right side of this point induce costs (per unit of damage prevented - e.g. lives saved) which are larger than the marginal cost.

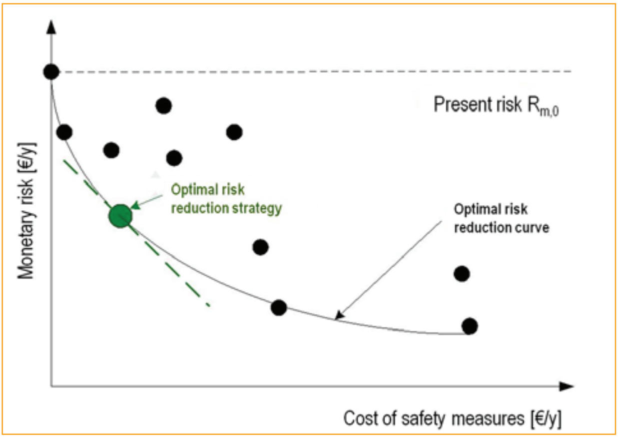

FIGURE 12 – RISK-COST DIAGRAM

It should be noted that the cost-effectiveness analysis is typically used for an optimisation process.

3.3.6. Evaluation of scenario analyses

Scenario analyses typically focus on the assessment of consequences, the consideration of probabilities is often neglected. However, scenario analyses may also be performed in combination with a system based approach, e.g. by selecting some relevant consequence scenarios of an event tree for a subsequent in-depth scenario analysis. In such a case the probabilities of the individual scenarios may be used as indicator for the relevance of the respective scenario when evaluating the results of the scenario analysis.

[2] Provided risk is expressed as monetary risk.

As there are many different ways to perform scenario analysis (depending on the problems to be investigated) a wide variety of different criteria for the evaluation of the results are applied.

Typical examples for scenario analysis and possible corresponding evaluation criteria in the context of road tunnel safety are as follows:

- investigation of evacuation of affected people in a tunnel emergency, e.g. by evacuation simulation (typical criterion: evacuation time);
- investigation of smoke distribution in a fire scenario (e.g. by CFD simulations) including the effects of various ventilation measures (typical criteria: tunnel length affected by smoke, visibility, flue gas concentrations);
- all kinds of consequence models for dangerous goods, such as explosion simulations or gas dispersion models (typical criteria; pressure values, gas concentrations, fatalities);
- investigation of emergency response in time steps, including development of event, reaction of safety systems, reaction of operator, reaction of people involved in the tunnel, intervention of fire brigade etc. (typical approach for evaluation: expert judgement with qualitative criteria).

In practice the evaluation of the results of a scenario analysis is often done by a comparison of the resulting consequences/risks for two similar scenarios with one considering the influence of a specific safety measure, for example, the development of a fire in a specific tunnel with or without a fire suppression system.

3.4. QUANTITATIVE EVALUATION OF INDIVIDUAL RISK

3.4.1. Definition of individual risk

Individual risk is the risk experienced by a single individual which is expected to sustain a given level of harm from realisation of specified hazards in a given time period (*figure 13, following page*). The number of people exposed to the hazard does not have any impact on the value of the individual risk.

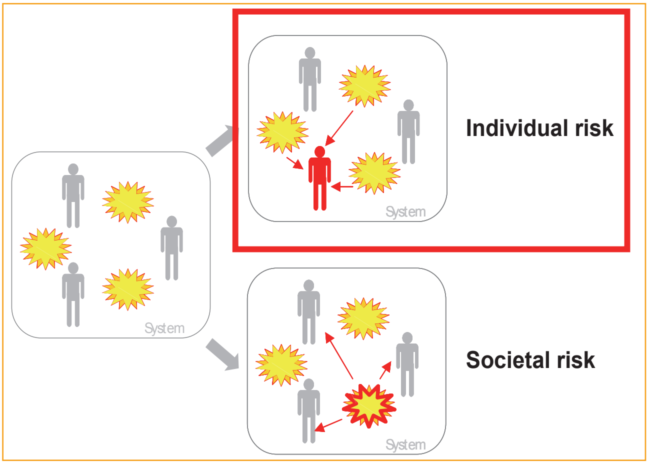

FIGURE 13 – INDIVIDUAL RISK

It should be noted that it is more common to evaluate risk in terms of societal risk and there are only a few applications of risk evaluation based on individual risks for tunnels (e.g. in the Netherlands).

3.4.2. Representation of individual risk

From a mathematical point of view, the probability of a consequence can be subdivided into the probability of the hazard scenario pS and the probability of the exposure to this scenario p_E[3]. The consequences are usually described in terms of different damage indicators k (e.g. fatality, injury, physical loss, loss of production or income, etc.) and their vulnerability λ_k (e.g. the vulnerability of a person can be expressed as lethality).

$$r_i = p_i * C_i = p_s * p_E * k * \lambda_k \quad (4)$$

Besides the definition of individual (fatality) risk (ri) as in equation (4) there are other terms and other definitions in parts, e.g.:

- loss of life expectancy,
- fatal accident rate (FAR),
- mortality rate.

[3] Another approach is to calculate the (average) individual risk based on the assessment of the societal risk and the number of people exposed. For such an approach, the influencing factors such as risk aversion are taken into account too.

3.4.3. Evaluation of individual risks

For individual risk (r_i) an upper limit can be defined based on statistics. As for the evaluation of societal risk according to Merz [15], the model of the four risk cases – distinguishing between voluntary and involuntary risks – can be applied.

In this case, the principle for the definition of acceptability criteria is based on the individual risks caused by all the activities in everyday life. The resulting risk caused by a certain additional activity – such as driving through a tunnel – must not increase the individual risk of everyday life substantially.

The maximum individual risk of losing life by a hazard usually ranges between 10^{-2} per year for a voluntary risky activity (e.g. parachute jumping) to 10^{-5} per year for an involuntary risk (e.g. nuclear reactor accident). Considering the criteria according to the concept of risk cases (*figure 4*) Bohnenblust and Slovic [16] formulated the four levels of acceptance for individual risk in *figure 14*.

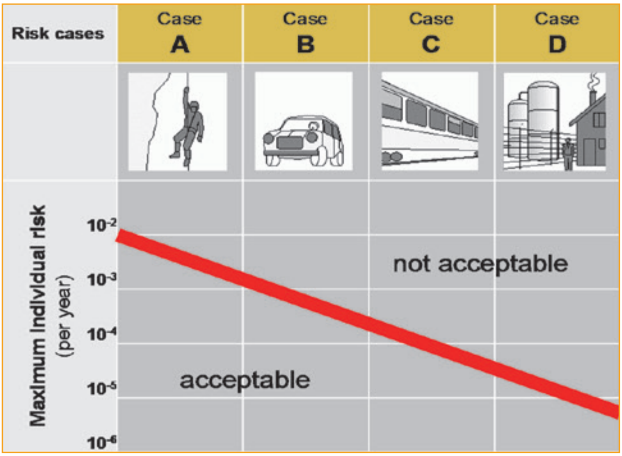

FIGURE 14 – CRITERIA FOR INDIVIDUAL RISK ACCORDING TO BOHNENBLUST AND SLOVIC [16]

4. RISK EVALUATION STRATEGIES – PRACTICAL APPROACHES

In the following subchapters the principles of risk evaluation described in *chapter 3, page 19,* are presented more in detail in the context of practically applied approaches. Additionally, practical examples are given for better illustration. These examples focus on the demonstration of methodical aspects and do not intend to present risk analysis results of general significance; hence it is not possible to draw conclusions for other tunnels or other, even similar problems on the basis of these results.

4.1. EXPECTED VALUE – APPLIED AS ABSOLUTE RISK CRITERIA

Definition of approach

The results of a risk analysis (system based approach) – expressed as expected risk value (e.g. expected number of fatalities/year for the tunnel investigated) are compared to a predefined target value. If the risk of the tunnel investigated is equal or below this target value, it is acceptable, if it is exceeded, then further action has to be taken.

Typically this approach is applied as a first step in a more complex step-by-step evaluation procedure. As for all absolute risk criteria, the magnitude of the predefined target value is strictly linked to the methodology applied for the risk analysis (because of fuzziness of risk analysis results) and cannot be used for other applications without a thorough check of applicability. The risk criteria (target values) can be set as overall criteria (valid for one tunnel) or in a normalised manner (valid per tunnel km).

It is possible to also include risk aversion into this approach by sub-dividing the expected value into several consequence classes and applying different weighing factors for different consequence classes (increasing factors for share of risk of accidents with increasing consequences – *chapter 3.2, page 20*). Thus more emphasis is put on accidents with higher consequences; of course this approach also needs to take account of the definition of the respective target values.

Another option is to define several target values for partial risks (instead of only one for the overall risk) whereas each target value is allocated to a specific partial risk (e.g. risk of specific scenarios). The risk criteria are only fulfilled if all partial risk values are below their respective target value; this approach allows a more specific risk evaluation including the option to set stricter target values for specific scenarios.

Practical application

A typical application for this approach is the evaluation of the risk of transport of dangerous goods through road tunnels. Various countries have developed different evaluation procedures; one common characteristic of these procedures is the use of a step-by step process, with the first step focussing on the separation of critical and non-critical tunnels. For this purpose, absolute target values for the expected value are used as 'relevance criteria'. If the calculated expected values fall below that limit it is ensured that other risk acceptance criteria are not violated; hence the risk is acceptable and no further investigations and no measures are required (*figure 15, following page*). The objective of this step is to identify at an early stage the non-critical tunnels in order to facilitate decision-making and to minimise the expenditure for safety investigations (e.g. for defining transport limitations for specific substances in the context of the implementation of ADR tunnel regulations, [4]). Such an approach is for example applied in Austria [18], France, Germany [19] and Greece; typical limits for such relevance criteria are given in the table in *figure 16* below:

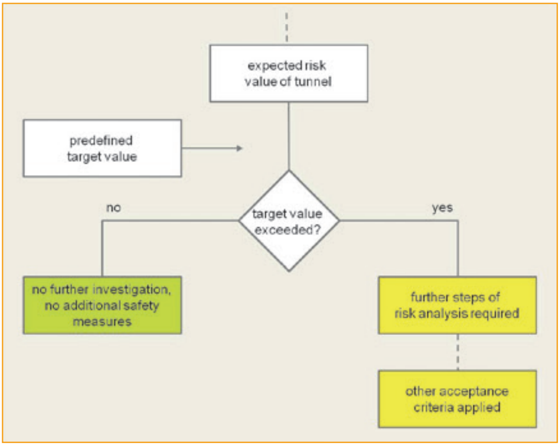

FIGURE 15 – EVALUATION OF DANGEROUS GOODS TRANSPORT RISK FOR TUNNELS

Country	overall EV	specific EV	linked to method	Comment
Austria	1 . 10^{-3} f/y	-	DG-QRAM	valid per tunnel
France	1 . 10^{-3} f/y	-	DG-QRAM	valid per tunnel
Germany	6,2 . 10^{-3} f/km x y	per scenario group: fire 5,0 . 10^{-3} f/km x y fire + explosion 2,2 . 10^{-3} f/km x y explosion 1,0 . 10^{-6} f/km x y toxicity 4,0 . 10^{-4} f/km x y	DG-QRAM	valid per tunnel km
Greece	1 . 10^{-3} f/y	-	DG-QRAM	valid per tunnel

FIGURE 16 – TYPICAL TARGET VALUES (EV) FOR RELEVANCE CRITERIA FOR DANGEROUS GOODS-TRANSPORT THROUGH TUNNELS (DANGEROUS GOODS TRANSPORT RISKS ONLY)

Figure 16 shows that evaluation criteria for Austria [18] and Greece rely on the French approach for which the overall EV was fixed at 10^{-3} fatalities per year whereas the German approach is based on different aspects. In the German approach, the overall EV is fixed at 6.2 * 10^{-3} fatalities per year and per kilometre [19]. Due to the fact that the overall EV is mainly dominated by the influence of fires (which are the most relevant dangerous goods scenarios in terms of frequencies) separate target values for other scenario types were determined (based on the experience gained in the past). Even though these scenarios only have a small influence on the resulting overall values, they can lead to high consequences, even significantly higher than fire scenarios.

Practical experience and discussion

This approach is easy to apply because it delivers unambiguous results. It shall be noticed however that risk evaluation based upon an absolute expected value is a rather general approach and - without specific precautions – does not take into account specific aspects such as:

- information on accident consequences (accidents with very low probability/very high consequences only contribute to a minor extent to the expected value);
- information on different damage effects (e.g. mechanical, fire, etc.).

These deficiencies may be overcome by including risk aversion, defining separate target values for specific scenario groups, depicting the share of different damage effects in the expected value and/or strictly limiting the use of this approach to clearly defined applications (as it is done in the example shown above).

Another problem – as for any absolute risk acceptance criteria - is the definition of the absolute target values for the expected value; such a value should be based upon a comprehensive study (benchmarks could be accepted risks in comparable systems, sensitivity analysis for various practical examples combined with expert judgement) and the results should be discussed in a group including all relevant stakeholders. This problem is complicated by the fact that an absolute criterion is linked to a specific methodology – hence it is necessary to clearly define the risk analysis methodology to be used and to limit the application of a specific criterion to this specific method.

4.2. EXPECTED VALUE – APPLIED AS RELATIVE RISK CRITERIA

Definition of approach

The results of a risk analysis (system based approach) expressed as expected risk values for two or more alternatives are compared to each other in order to select an alternative which represents a lower level of risk. This concept can be used for different applications, such as evaluation of additional safety measures (as explained in *section 4.4, page 45*) or risk evaluation by means of a *“reference tunnel”*.

In the concept of a *“reference tunnel”* a characteristic tunnel is defined as acceptable in terms of risk by the stakeholders or by regulations and used as reference case. The *“reference tunnel”* is typically defined as a tunnel which assures that the safety objectives are fulfilled in an equivalent way, taking into account all prescriptions of safety-relevant regulations, (without necessarily taking into account the performance of the safety measures).

The *"reference tunnel"* is subject to a risk analysis and the calculation of an expected value which is used as reference value to be compared to that calculated for the real tunnel. The comparative method is independent from absolute acceptability risk criteria and is compatible with the *"Globally At Least Equivalent"* (GALE) principle of risk acceptability.

The results of risk evaluation are strictly linked to the risk model adopted. Specifically, the risk evaluation depends on the uncertainties pertaining to the input parameters and the risk quantification models adopted. The definition of expected risk value and the concept of reference tunnel which characterise the comparative method reduce the effects of the uncertainties on the risk evaluation results, if the same model is applied in both cases.

The relative risk criterion does not require decisions on absolute reference values; the accepted risk is implicit in the definition of the reference tunnel.

As for absolute criteria it is also possible to include risk aversion into this approach by sub-dividing the expected value into several consequence classes and applying different weighing factors for different consequence classes (increasing factors for share of risk of accidents with increasing consequences – *section 3.2, page 20*). Thus more emphasis is put on accidents with higher consequences. Another option is to define several reference values for partial risks (instead of only one for the overall risk) whereas each reference value is allocated to a specific partial risk (e.g. risk of specific scenarios). The risk criteria are only fulfilled if all partial risk values are below their respective reference value; this approach allows a more specific risk evaluation including the possibility to find alternative measures specific to critical scenarios.

Practical application

A possible application for this approach is the evaluation of alternative measures to compulsory safety measures. Some EU countries developed different evaluation procedures; one common characteristic of these procedures is the definition of a reference tunnel as a tunnel compliant with the EU Directive 2004/54/EC which defines the minimum safety requirements for road tunnels on the trans-European road network in terms of prescriptive safety requirements [2].

The main difference between the approaches is the type of hazards considered for calculating the risk: road accidents, fires, accidents involving dangerous goods. The consideration of different hazards characterized by different risk values may lead to different safety measures in the risk evaluation process.

The application of the relative risk comparison does not assure the respect of absolute values; the risk level of the reference tunnel should be assumed or demonstrated to be acceptable.

Such an approach is for example applied in Austria and Italy where the main characteristics of the analysis and criteria are given in the table below.

	Hazards	Reference tunnel
Italy [20]	Fires Road accidents with fires Toxic Releases Liquid Spillages	A virtual tunnel fully complying with the minimum safety requirements of the EU Directive with predefined performance for safety systems. No indications are given for length and traffic characteristics.
Austria [21]	Road accidents with mechanical effects Vehicle fires Road accidents involving dangerous goods (limited approach only)	A tunnel of the same length, type and traffic characteristics fully complying with the minimum safety requirements of the EU Directive.

The Austrian method is based on the philosophy that a tunnel is sufficiently safe, if its risk is lower than the risk of a reference tunnel which fulfils all the requirements of the EU-Directive, including benchmark parameters defined in *annex 1, page 64,* (such as a longitudinal gradient of 3% or a percentage of HGVs of 15%). This approach of risk evaluation by relative comparison at the level of the expected value is complemented by an evaluation of the absolute magnitude of risk resulting from a risk analysis, which is applied for a classification of tunnels into 1 of 4 danger classes [22]. The danger class of a tunnel is used for the definition of requirements for tunnel equipment according to the Austrian tunnelling guidelines.

Since Italy has many tunnels with special characteristics, the Italian Risk Analysis Method (IRAM) requires an absolute risk evaluation with FN curves to be performed for all tunnels before applying the comparative criteria in order to demonstrate that the FN curve lies under the tolerability limit [23]. The comparative criterion is actually adopted as a simplified method to fulfil the ALARP risk reduction criteria. The comparison is done between the Expected Damage Values as derived from the defined integral of FN curves calculated by a well-defined methodology.

The main limit of this risk evaluation method is the definition of the reference tunnel which to a certain extent relies on expert judgement in particular when it represents a prescriptive regulation compliant tunnel and the underlying regulation does not define all the risk related parameters. The definition of a reference tunnel for comparing structural measures with alternative safety systems may consider systems reliability and efficiency that may not be found in prescriptive regulations. The definition of reference performance for safety systems can be derived from design good practice or assumed as ideal: expert judgement, simplifications and uncertainties can affect the results of the risk evaluation.

Practical experience and discussion

The approach is easy to apply but can deliver ambiguous results that derive from the adoption of a unique number for representing risk and from the definition of a reference tunnel. It shall be noticed that risk evaluation based upon a relative expected value is a rather general approach and - without specific precautions – does not take into account specific aspects such as:

- information on accident consequences (accidents with very low probability/very high consequences only contribute to a minor extent to the expected value);
- information on different damage effects (e.g. mechanical, fire, etc.);
- information on the uncertainties associated to the risk.

As for absolute criteria some of these deficiencies may be overcome by including risk aversion, defining separate reference values for specific scenario groups, depicting the share of different damage effects in the expected value and/or strictly limiting the use of this approach to clearly defined applications.

Another problem – as for any relative risk acceptance criteria - is the definition of the reference tunnel characteristics and the hazards to be considered. Such a tunnel should be based upon a comprehensive study (sensitivity analysis for various practical examples combined with expert judgement) and the results should be discussed in a group including all relevant stakeholders.

The adoption of higher order statistical parameters (standard deviation, skewness, and kurtosis) may increase the level of information of the risk values associated to the tunnel and could help in the definition of tolerances, given that these parameters can be derived from a sound data basis.

If the same risk model is applied for both the investigated and the reference tunnel the influence of inaccuracies/fuzziness is reduced (same systematic inaccuracies, more or less same fuzziness of input data).

The raw comparison of two tunnel configurations without considering the effectiveness of systems and uncertainties could bring ambiguous results, in particular when there are slight differences between the reference tunnel value and investigated tunnel value since the evaluation is made on the basis of the confrontation of two numbers that are unable to describe in a complete manner the risk associated with a complex system.

4.3. FN CURVE – APPLIED AS ABSOLUTE RISK CRITERIA

Definition of approach

The results of a (system based) risk analyses represented as an FN curve are compared to a predefined absolute criteria in terms of an acceptability curve in the FN diagram. Therefore the risk analysis methodology has to provide quantitative assessments for different scenarios in terms of frequencies and consequences. For some methodological approaches several risk indicators are analysed. Thus there is the need for determination of acceptability curves in the FN diagram or to use standardised units of consequences for the different risk indicators.

Practical application

The application of acceptability curves in the FN diagram as a basis for evaluation of risk in road tunnels is used in a number of different countries, as shown in *figure 17 to figure 22*. It has to be noted that some of the shown reference criteria are valid for the risk of the overall traffic whereas some criteria are only valid for the risk of transport of dangerous goods through road tunnels. Criteria for transport of dangerous goods may be more restrictive than those for the overall traffic. Additionally it shall be stressed that some reference lines are strictly linked to a specific method or risk model. In the following a short summary of the presented evaluation criteria for each application is given.

Netherlands

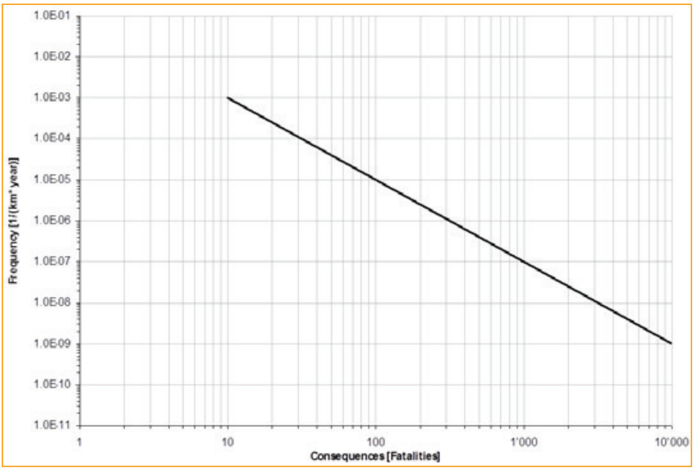

FIGURE 17 – DUTCH RISK CRITERIA FOR ROAD TUNNELS

In the Netherlands the policy is that, in principle, there are no restrictions for the transport of dangerous goods on the main road network with exception of underwater tunnels. Most of the underwater tunnels are category C tunnels and some of them category D (according to ADR tunnel regulations [4]). The reference criterion is:

$F = 0{,}1 \cdot N^{-2}$ per kilometre per year, for $N > 10$ fatalities

This criterion is not a constraint curve but a target value. Deviation is possible if sufficient arguments for the deviation are provided. The risk calculations are made for the expected use in the future (usually a period of approximately 15 years is used).

Austria

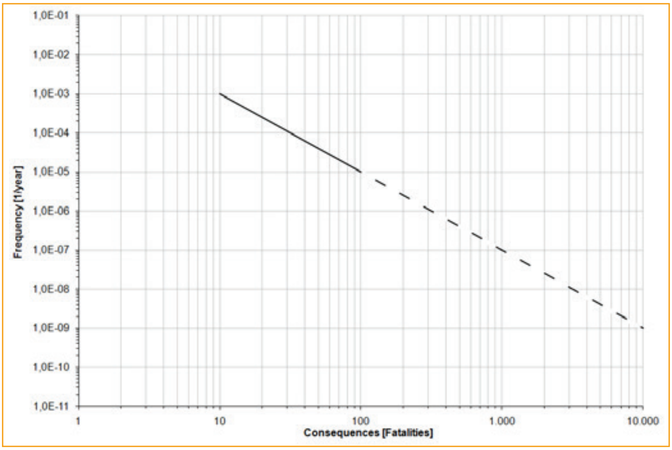

FIGURE 18 – AUSTRIAN RISK CRITERIA FOR DANGEROUS GOODS TRANSPORTS THROUGH ROAD TUNNELS [18]

In Austria, the guideline RVS 09.03.12 [18] *"Transport of dangerous goods through road tunnels"* defines the following reference line as absolute risk criteria in the FN diagram:

$F = 0{,}1 \cdot N^{-2}$ for $N > 10$ fatalities

This reference line is only applied in the second stage of a multistage evaluation procedure for the risk of dangerous goods transport through road tunnels and is strictly linked to the risk model DG-QRAM [3]. The reference line is valid for a 1 km long road tunnel; it is adapted to tunnels with other lengths according to the formula:

$F = 0{,}1 \cdot N^{-2} \cdot L^{0{,}5}$ for $N > 10$ fatalities

For the definition of this reference line the following aspects were taken into account:

- risk level of a reference system (aviation),
- characteristics of the risk model DG-QRAM [3],
- characteristics of the Austrian road tunnel collective,
- results of test calculations for typical model tunnel.

Italy

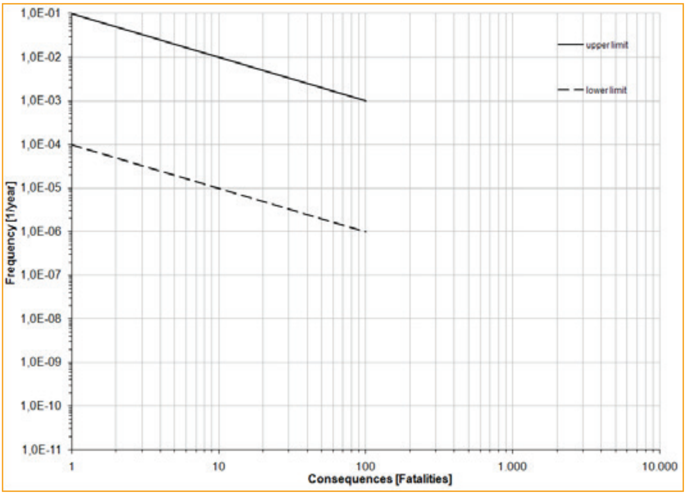

FIGURE 19 – ITALIAN RISK CRITERIA FOR ROAD TUNNELS [20]

For the evaluation of the resulting risk for a tunnel according to the Italian Risk Analysis Method (IRAM) the following acceptability criteria are defined as absolute risk criteria in an FN diagram [20]:

for the upper limit according to the following function:

$$F = 0.1 \cdot N^{-1} \qquad \text{for } N \geq 1 \text{ fatality}$$

if the resulting FN curve is above this upper limit, the risk will be evaluated as not acceptable.
for the definition of acceptable risk a lower limit is used:

$$F = 10^{-3} \cdot N^{-1} \qquad \text{for } N \geq 1 \text{ fatality.}$$

The area between the upper limit and the lower limit defines the area of application of the *“ALARP”* principle (*As Low As Reasonably Practicable*). The acceptability line is valid for the tunnel or – in case of a tunnel with two separate tubes – for one tunnel tube.

Czech Republic

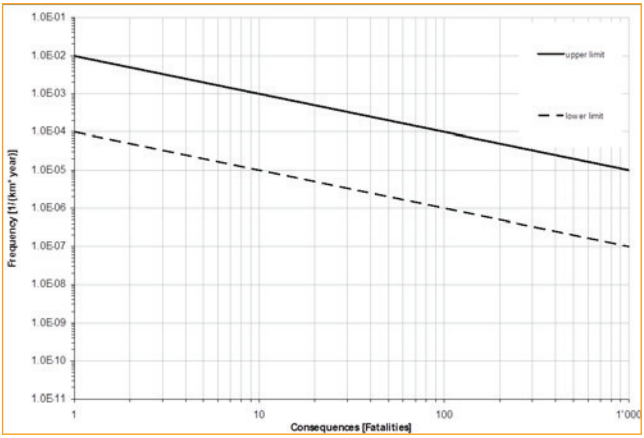

FIGURE 20 – CZECH RISK CRITERIA FOR ROAD TUNNELS

The reference criteria used in the Czech Republic are not based on any legal requirement. The criteria form a general recommendation for Czech road tunnels, formulated on the basis of knowledge and experience in international cooperation [24]. The reference criteria are recommended for a 1 km long road tunnel (per 1 year) and are applicable with regard to the risk of the overall traffic using the tunnel, without any further specification of the load being transported. The recommendation defines the following reference lines as risk criteria in the FN diagram:

upper limit:	$F = 0{,}01 \cdot N^{-1}$	for $1 \leq N \leq 1000$ fatality,
lower limit:	$F = 10^{-4} \cdot N^{-1}$	for $1 \leq N \leq 1000$ fatality.

Where F is the cumulative probability of occurrence of incidents with the number of casualties being greater than or equal to the number N. Similarly to other systems, the Czech criteria also use the ALARP principle.

Switzerland

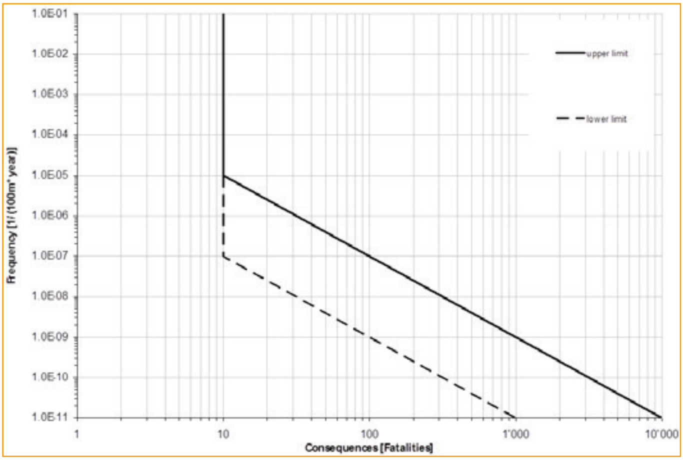

FIGURE 21 – SWISS RISK CRITERIA FOR DANGEROUS GOODS TRANSPORTS (INCLUDING ROAD TUNNELS) [25]

In Switzerland, the *"Ordinance on Protection against Major Accidents"* requires among other aspects the assessment and evaluation of risks caused by the transport of dangerous goods on transit roads including tunnels. The purpose of this ordinance which came into force in 1991 is to protect the public and the environment against serious damage resulting from major accidents caused by the storage, loading/unloading and transport of dangerous goods and to inform the public about existing risks. The procedure to control and assess relevant hazard potential and risks consists of two steps. In the first step, the owner of a tunnel submits a summary report containing an assessment of hazards. On the basis of the hazard assessment in the summary report, the enforcement authority decides whether, in a second step, a quantitative risk assessment has to be performed. If this second step is needed, the risk of incidents in tunnels and corresponding effects is expressed quantitatively in terms of the frequencies of the accident scenarios, represented as FN curves, normalised for 100 m. The responsible authority evaluates the risk as follows:

- if the cumulative frequency curve enters the unacceptable domain the owner of the tunnel is asked to reduce the risk, else the authority is empowered to take actions including operational restrictions;
- if the cumulative FN curve is between the upper and the lower limits (ALARP), the enforcement authority will measure the interests of the tunnel owner against the needs of the public and the environment for protection from accidents. Depending on the outcome of these considerations, the risk has to be reduced to a level defined by the authority;

- if the cumulative FN curve lies in the acceptable domain all through, the risk assessment procedure is complete. However, the owner must still take all appropriate measures to reduce risk.

Germany

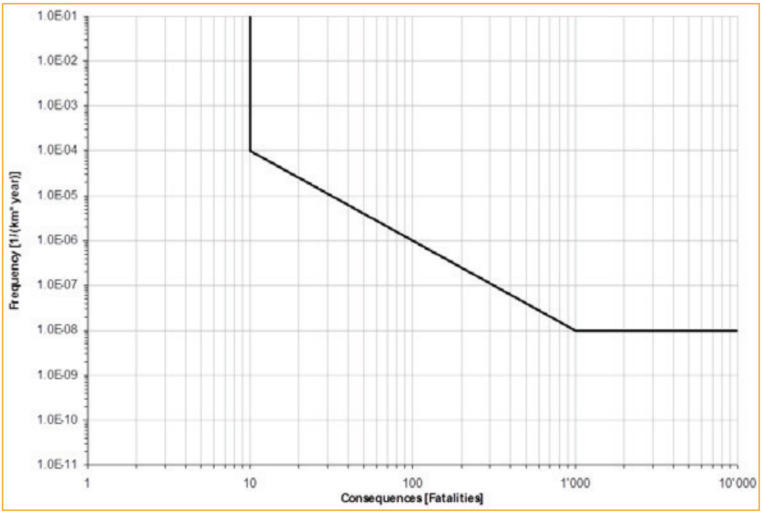

FIGURE 22 – GERMAN RISK CRITERIA FOR DANGEROUS GOODS TRANSPORTS THROUGH ROAD TUNNELS [19]

In the course of the implementation of the ADR tunnel regulations [4] a specific methodology for the analysis and evaluation of risk of transport of dangerous goods was developed within a research project. The developed procedure for a risk-based classification of road tunnels in categories according to ADR consists of two stages. In a rough evaluation (stage 1, see also evaluation criteria in *figure 16*) a tunnel will be checked in two steps to determine whether it can allow all hazardous goods transports or not. When the hazardous goods risks are evaluated as being too high by means of the simple models of stage 1, the tunnel has to be examined in-depth. The resulting risk has to be represented as an FN curve (normalised for 1 km) for the analysed scenarios and the overall risk. If the determined risk is below a comparative curve based on empirical values, the tunnel can allow all hazardous goods transport. If the risk curve is above the comparative curve, the tunnel will be classified according to requirements, i.e. it will be blocked for hazardous goods transport with the appropriate tunnel restriction code and constructional, technical or organisational measures will be taken respectively to reduce the risk.

Practical experience and discussion

The evaluation based on acceptability curves in an FN diagram applied as absolute risk criteria delivers unambiguous results. Furthermore it provides more detailed information about the risk profile and the relevance of specific scenarios. It should be noted that for practical reasons, uncertainties in the risk assessment are normally not taken into account in terms of acceptability curves. Therefore the discussion of sensitivities of the resulting risk – especially if the cumulative frequency curve is near the acceptability curve – is important.

Concerning the deficiencies of this approach it should be noted that for the evaluation based on absolute criteria for FN curves, the definition of the acceptability curves/ boundaries can be a long-term process in which all stakeholders should be involved. Furthermore, as experience shows, the evaluation of risks for which the cumulative FN curve is in the ALARP area is often not clear and the interpretation of appropriateness of additional safety measures is often not treated in a consistent way.

4.4. FN CURVE – APPLIED AS RELATIVE RISK CRITERIA

Definition of approach

The results of (system based) risk analyses represented as FN curves of two or more alternatives are compared to each other in order to select an alternative which represents a lower level of risk. An alternative is regarded as better if the FN curve representing this alternative lies (continuously) below the curve representing the other alternative and the differences between the compared FN curves exceed the inaccuracies. However, in a relative approach inaccuracies may have less influence on the outcome of risk evaluation, especially if the compared FN curves were calculated with the same risk model using more or less the same input data. This risk evaluation strategy may be combined with the concept of a reference tunnel as described in *chapter 4.2, page 35*.

This approach typically constitutes one step in a more complex step-by-step evaluation procedure:

- **first step:** initial risk analysis to determine the risk of a given basic option, which is subject to further investigations (e.g. in order to reduce risk by additional safety measures);
- **second step:** calculation and comparison of FN curves for different possible options to be investigated (basic option, for which the question occurs and possible alternatives);
- **third step:** choice of an option that presents a level of risk that is considered lower than the other possible options. At that level of investigation, other criteria may also be considered. Especially in a situation when no clear decision can be made with this comparative approach (same level of risk for all possible options), it may

be necessary to define new options to compare, or to take other criteria into account (e.g. cost in a cost effectiveness approach, expected value as second risk criteria).

Practical application

Typical applications of this comparative approach are:

- assessment of effects (on risk) of additional safety measures which can be applied to reduce the risk of a given basic alternative;
- risk evaluation by comparison of the FN curve of a given tunnel to the FN curve of a reference tunnel;
- choice of a tunnel category according to ADR regulation [4], for instance comparison of different options regarding authorisation of dangerous goods transport in a given tunnel according to ADR categories: possibilities to escort HGVs carrying dangerous goods in the tunnel, possibilities to forbid HGVs carrying dangerous goods during some periods of time, etc.

Two examples are presented (for the first and the third application):

First example
In a 600 m long tunnel with unidirectional traffic, with one emergency exit in the middle and without mechanical ventilation additional safety measures have to be assessed in order to select the most effective one in terms of risk reduction. One risk mitigation measure investigated is the implementation of a longitudinal ventilation system.

The risk of the tunnel in the initial state and with this additional safety measure depicted as FN curves is shown in *figure 23*. As additional decision criteria, the respective expected risk values (fire risk only) are used.

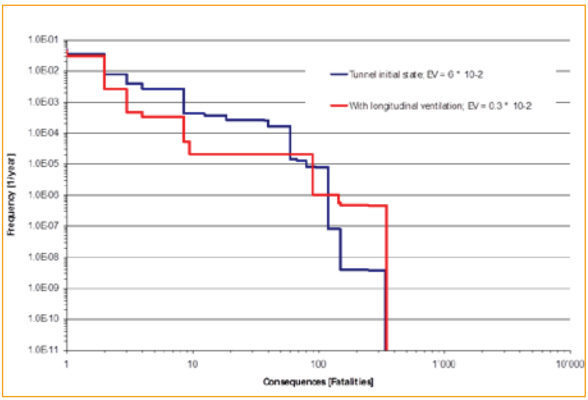

FIGURE 23 – FN CURVES – REPRESENTING THE TUNNEL IN THE STATE AND WITH ADDITIONAL SAFETY MEASURES (EXAMPLE)

The decision process can be described as follows. Although the two FN graphs (blue: initial tunnel – red: longitudinal ventilation) cross each other it can be stated clearly that there is a big risk reduction due to the longitudinal ventilation, because the higher risk with ventilation only refers to scenarios with very low frequencies (10-6 and lower) and is due to a faster smoke distribution in the very rare situation of a traffic jam inside the tunnel, which also can be prevented by organisational measures. The EV indicates clearly the improvement due to the longitudinal ventilation.

Second example

The transport of dangerous goods through a tunnel has to be investigated according to the ADR tunnel regulations [4]. The following graphs represent the risks due to dangerous goods transport in the following situations:

- **category A:** All Dangerous goods are allowed and go through the tunnel route;
- **category B:** Dangerous goods with C, D or E restriction codes go through tunnel route, and dangerous goods with B restriction code go through an alternative route. The curve presented is the summation of:

  – risks on the tunnel route of dangerous goods that are allowed through tunnel in this situation, plus
  – risks on the alternative route, due to dangerous goods that are banned on tunnel route;

- **category C:** Dangerous goods with D or E restriction codes go through tunnel route, and dangerous goods with B or C restriction code go through an alternative route. The curve presented is the summation of dangerous goods risks on the tunnel route and on the alternative route;
- **category D/E:** All Dangerous Goods go through the alternative route.

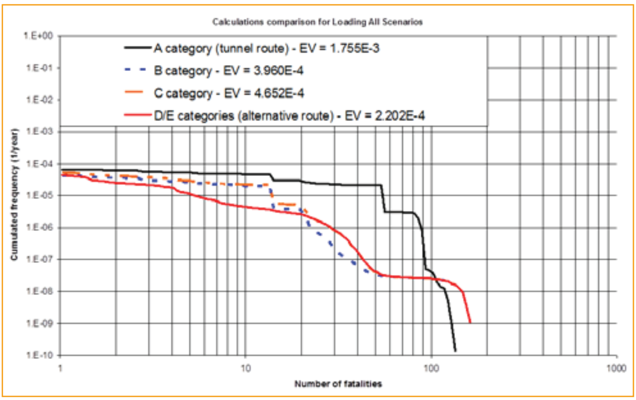

FIGURE 24 – FN CURVES REPRESENTING DIFFERENT OPTIONS REGARDING TUNNEL CATEGORIES FOR DANGEROUS GOODS-TRANSPORT THROUGH TUNNELS (DANGEROUS GOODS TRANSPORT RISKS ONLY)

Interpretation of results shown on the figure above is difficult because the curves cross each other. In cases such as this, interpretation of FN curves alone is often not sufficient, and interpretation of the EV is also necessary.

In the present example, one can consider that:

- the curves of B, C and D/E category options are too close to take a decision,
- the curve for A category is close to the 3 preceding ones both for scenarios with a small number of victims (and higher frequencies) as well as for those with major consequences (and lower frequencies). However, a significant difference in frequencies is shown for scenarios with medium consequences (e.g. a difference of more than 2 orders of magnitude is shown for consequences with 50 fatalities or more).

The conclusion in this situation is that the choice of A category for the tunnel should be avoided, but that it is not possible to choose between the other possible options (B category, C category or D/E category) on the basis of this comparison only (graphs are too close together – hence no significant difference in risk). Therefore other criteria must be considered to take a decision. The analysis of the EV confirms this result based on FN curves.

It is usually the case that curves representing B, C or D category will sit between curves corresponding to A & E categories. It is especially the case when oil transport (motor spirit, gasoline) represents the majority of the dangerous goods transported on a given route. However, it is not always the case: intermediate curves could represent a situation where risk has been mitigated, for example where there are more toxic liquids than usual in the dangerous goods traffic, and where the tunnel route is designed to effectively collect drainage liquids.

Practical experience and discussion

This comparative approach is very useful for the risk-based comparison of alternatives and decision making, if the results of a risk analysis are depicted as FN curves. As demonstrated above it can be used for the selection of additional safety measures as well as for the selection of preferable dangerous goods transport routes.

However, the following shortcomings of this approach must be considered:

- FN graphs are often difficult to interpret and need to be read very carefully; those graphs are not linear but are often represented in a double logarithmic scale with considerably different scales in the horizontal and vertical direction;
- if inaccuracies are significant and/or the range of differences of the compared options is lower than the range of inaccuracies and/or the comparison delivers

ambiguous results (e.g. the FN curves cross each other several times), then it is difficult to choose between the studied options.

To overcome the shortcomings of this approach, this type of risk evaluation strategy needs to be combined sometimes with other approaches (such as cost/benefit analysis) or additional criteria (such as supplemental assessment of expected values). An example of a risk evaluation process using expected values and/or FN curves (as absolute criteria) as additional criteria in a step by step procedure is the following:

- **step 1:** the EV or FN curves for the different options are compared to absolute risk criteria to assess if the level of risk of these options is neither negligible (verification that the calculated level of risk is higher than a given low threshold) nor unacceptable (verification that the calculated level of risk is lower than a given high threshold);
- **step 2:**

  – if some options are not in the unacceptable area, and if all options are not in the negligible area, a comparison is performed between the options that present an acceptable level of risk, so as to choose the one that presents the lowest level of risk;
  – if all options are in the negligible area, then the estimated risk is not a criterion for a choice between different options, and other criteria must be considered;
  – if all options are in the unacceptable area, then new options should be considered, so as to find at least one option that can be considered as acceptable.

4.5. COST-EFFECTIVENESS

Definition of approach

The cost-effectiveness approach considers the efficiency of safety measures compared to their potential for risk reduction. As well as proving the efficiency of safety measures from an economical point of view, this approach can be applied as acceptability criteria. Thus it ensures that the resources spent to reduce risk are spent in such a way that an optimised level of safety is obtained. Furthermore it can be applied for the comparison and evaluation of different safety measures

Practical application

The German approach for the implementation of the requirements for risk analyses in the German guideline RABT 2006 [26] comprises among other aspects the cost-effectiveness approach. It is a part of the planning process for safety measures if needed, e.g. if alternative safety measures have to be considered when technical/ infrastructural requirements of the RABT 2006 [26] are not fulfilled.

The main steps of the procedure are:

- alternative safety measures or combinations thereof have to be identified.
- for the planned, alternative measures, the risk-reducing effect as well as the costs resulting from the implementation and operation must be determined. The annual costs K_{year} must be determined to evaluate the planned alternative measures according to cost-effectiveness. These comprise of

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

The resulting, annual costs can be calculated as follows:

$$K_{year} = K_{invest} \cdot \frac{(1+d)^n \cdot d}{(1+d)^n - 1} + K_{operating}$$

where:

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

The costs of measures (specific per project) have to be converted to annual costs in the same way as risks or risk reductions.

- For the determination of the monetary (fatality) risk, marginal cost of €10 million for fire scenarios and €5 million for collision scenarios per saved life are applied. For infrastructure risk, a marginal cost of €3 per €1 of prevented infrastructure damage is applied. Risk aversion factors φ are also included;
- for the assessment, the cost of the initial investment and the cost for the annual operation and maintenance have to be considered. Based on these elements the annual cost can be derived, including life span of the analysed safety measure(s) and an annuity factor;
- fFor the cost-effectiveness ratio (K/R) where:

  – K: annual costs [€/year]
  – R: reduction of monetary risk [€/year],
  – the following criteria have been defined for the decision-making:
  – $K/R < 1$: Safety measures should be implemented
  – $1 \leq K/R < 2$: The implementation to be checked by case-on-case study
  – $K/R \geq 2$: Safety measures not cost-effective

Practical experience and discussion

As publication of the methodology for the implementation of the requirements for risk analyses in the German guideline RABT 2006 [26] was in summer 2009 there are only few practical experiences existing in Germany.

In other countries several practical applications exist, e.g. in the Netherlands [27]: an estimation of cost-effectiveness has been made for two practical cases. The first is a tunnel which is constructed near the city of Roermond as part of the A73 highway. It is constructed as a double tube tunnel (2x2 lanes) with a length of 2,040 m. The second example considers a feasibility study which is undertaken on the construction of a seven kilometre long double tube tunnel (2x3 lanes) to connect the two Junctions of the A6 and A9 highways near Amsterdam. Both are so called *"category 0"* tunnels, which means that no limitations for the transport of dangerous goods are applicable. The cost effectiveness of the installation of a sprinkler system has been investigated for these two tunnels. Based on experience, the costs of the sprinkler system are roughly estimated at 10 million Euro/km tunnel. The risk reducing effects of the installation of the sprinkler system have been analysed with the Dutch TUNPRIM model. With this quantitative risk analysis model the internal risks for the users was assessed. The study came to the conclusion that from the results of the cost effectiveness analysis, these safety measures are not preferable for these specific tunnels (of course, the conclusions for other tunnels might be different).

The application of cost-effectiveness approaches is a possible way to bring tunnel safety towards an optimum from an economic point of view. It helps achieve the maximum efficiency in terms of risk prevention and resources spent. As a deficiency – compared to the definition of acceptability criteria for EV or FN diagrams – the determination of marginal cost is often a difficult process and can only partly be based on scientific data in a narrower sense.

4.6. SCENARIO ANALYSES

Definition of approach

Scenario-based risk analysis is a useful tool, as a complement to prescriptive requirements, regulations and guidelines. For tunnels at the design stage, commissioning stage, and in particular for tunnels in operation, one important step in a safety investigation may be the definition of the reference condition, i.e. the objectives to be achieved in terms of interactive performance of the various safety systems. Scenario-based risk analysis can be used to investigate whether or not the system composed by the infrastructure reacts as safely as expected, with regard to the way it is used by road users (feedback of experience), the way it is operated, and the way rescue is organised. However, there is a big variety of different approaches for scenario-based risk analyses and therefore the definitions in this chapter cannot be exhaustive.

Practical application

For new tunnels, designed in accordance with detailed prescriptive requirements, there may be little need for discussion about infrastructure requirements and the related safety equipment. Nevertheless, questions can arise about organisation of supervision, operation and emergency response. But, prescriptive requirements for new tunnels are not systematically applicable to existing tunnels. That is why a specific process is needed, so as to define a reference condition that can be considered as acceptable regarding safety objectives. In this process, scenario-based risk analysis techniques may be applied as a tool for risk assessment. An example of such a process is illustrated below in *figure 25*.

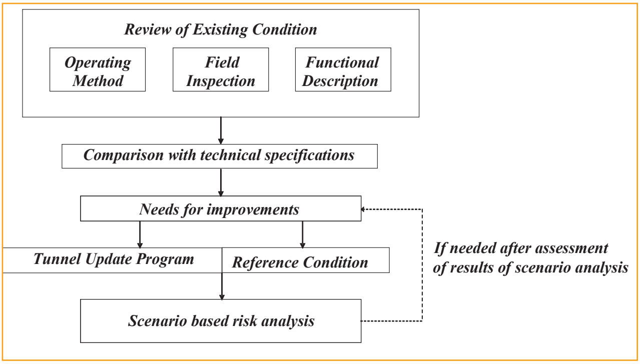

FIGURE 25 – EXAMPLE OF A PROCESS FOR TUNNELS IN OPERATION TO DEFINE AN ACCEPTABLE LEVEL OF SAFETY, APPLYING SCENARIO BASED RISK ANALYSIS

Space-time graphs are useful for the presentation of results of scenario analyses. In *figure 26, following page,* an illustration is given of a possible representation of temperature effects of a 100 MW HGV fire in a twin-bore tunnel with longitudinal ventilation.

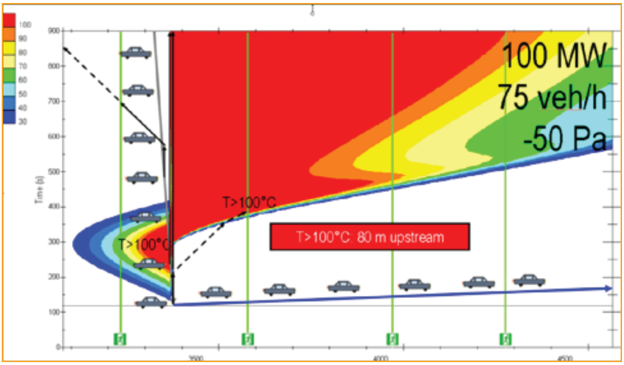

FIGURE 26 – EXAMPLE OF SPACE X TIME GRAPH REPRESENTATIVE OF A HGV FIRE

This graph shows that, once operated, the longitudinal ventilation is able to push the smoke downstream so that the vehicles blocked behind the fire are ultimately kept in a safe atmosphere. However, if the fire ventilation system is not operated rapidly, or if there is a significant adverse pressure between portals, then there is a risk of smoke spread upstream of the fire in the first few minutes.

During this first phase, road users trapped upstream of the fire could be infold by smoke until the jet fans are fully operational and smoke is pushed downstream. The consequences would then depend on:

- the initial conditions (traffic and difference of pressure),
- time to activate appropriate actions (especially jet fans),
- fire heat release rate;
- the number and behaviour of the users,
- the location of the fire.

This kind of situation with temporary backlayering potentially may occur in all tunnels with longitudinal ventilation and is generally considered acceptable in non-urban tunnels (because of the very low probability of a fully-developed fire under such very unfavourable conditions), provided that tunnel operator can guarantee a quick and appropriate response to the various possible emergency situations.

If not, the conclusion should be that complementary safety measures and/or provisions are necessary to improve the kind of situation illustrated by the scenario investigated. For instance:

- if relevant: addition of an Automatic Incident Detection (AID) system, as an assistance to the operator to quickly identify any traffic incident;
- modification of the procedure applied by the operator in case of an incident, so as to:

– firstly, start all the jet fans in case of any kind of unexpected event in the tunnel, prior to the qualification of the kind of unexpected event,
– then, qualify the unexpected event, and, if it has been proven that this unexpected event is not a fire, switch off the emergency ventilation system;

- install remote controlled barriers at each portal, so as to limit the number of vehicles trapped upstream in the vicinity of the fire.

Practical experience and discussion

Scenario-based risk analyses can provide a useful illustration of specific risks. Risk evaluation based on scenario analysis has advantages and disadvantages compared to risk evaluation based on system-based analysis.

The main advantages are the following:

- dealing with specific, well-defined situations allows a better understanding of the associated specific risks, for tunnel manager, tunnel operator and rescue services. Learning from such analyses can help in the preparation of appropriate emergency response plans;
- if necessary, such analyses allow adaptation of some parameters, from a design and/or an organisational point of view, so as to improve weak points and limit identified adverse effects;
- the representation of risks is illustrative and can be communicated more easily, without the *“black box”* effect.

The main disadvantages are the following:

- risk evaluation and risk acceptance is mainly based on expert judgment, which can vary from person to person;
- only a few situations can be investigated that way, even if the derived conclusions may take account of more generic situations than the specific ones that are investigated in a quantitative way;
- it is important to carefully select representative scenarios – otherwise the conclusions drawn may focus on wrong aspects.

5. LEGAL IMPLICATIONS OF RISK ANALYSIS

Risk evaluation is an essential component of decision making in personal, corporate and government contexts. Done well, a decision which includes a component of risk evaluation will provide a robust platform to make and if necessary explain a decision.

In all countries there are laws which regulate making professional decisions. The way in which a professional makes a decision, the matters which are considered relevant and the standard to be applied to the decision maker when making decisions varies from country to country and upon the nature of the decision itself.

When serious injury, substantial damage or economic loss occurs as a result of an incident in a tunnel a legal investigation is likely. Legal investigations always critically examine the decisions which have contributed to the nature, extent and occurrence of the events which are the subject of investigation. A risk evaluation often underlies such decisions, or is used subsequently as a means of scrutinising the earlier decision.

Important decisions may rely upon a process of risk evaluation. The weight to be attributed to risk evaluations in decision making requires an understanding of the uncertainties, deficiencies in data, subjective nature of opinions and the specific limitations inherent in the specific risk evaluation conducted.

These risk evaluation limitations should never be overlooked in the decision making process because risk evaluation is merely a tool to assist decision making – not an end in itself.

5.1. RISK EVALUATION AND LAWFUL DECISION MAKING

In a legal investigation into a decision the legal focus is on how a decision was made and is not as focused upon what the decision was. This is because in all legal systems decision makers are legally obliged to exercise due care and skill in making a decision. The legal test always revolves around the state of knowledge at the time of a decision, not the state of knowledge with the benefit of hindsight.

Although the standard expected of a decision maker in exercising due care and skill varies significantly between countries and the context of each specific decision, the principles to be applied remain generally consistent.

- Risk evaluation is not a substitute for making a more broadly informed decision. The results of risk analysis conducted are only one factor to be considered by a decision maker and are not a substitute for considering the specific issues necessarily raised by the decision in question;
- the strengths and weaknesses of any risk evaluation techniques utilised should be stated in the context of the specific scope and circumstances of the question at hand. The judgement of past decisions will only be made on the basis of what was known at the time, a decision will not be viewed with the benefit of hindsight.

In such circumstances it is recommended that for critical decisions that rely upon a risk evaluation process an explanation of the decision be kept which explains:

- the extent the results of a risk evaluation are relied upon and why;
- the relationship of the decision to the likelihood of undesirable events;
- an acknowledgement that there are always residual risks;
- the level of confidence in the results based upon the analysis conducted.

5.2. THE LEGAL ROLE OF A RISK ASSESSMENT

A decision maker is not bound to follow the results of a risk assessment. Indeed in many legal systems to solely rely upon the findings of a risk evaluation process would itself create an unlawful decision. The results of any risk assessment are but one of a number of matters to be considered by a decision maker. Conducting risk assessments with the principle objective of supporting a decision which has already been taken is of a high legal risk because it brings into question the objectivity of the evaluation process.

5.3. LANGUAGE

The technical language used in the documentation of the analysis and findings during a risk evaluation must be mindful and sensitive to the culture and traditions of the society in which the assessment is being conducted. When considering the relationship between risk mitigation strategies, their cost and the level of risk to people, the words used are critical because legal systems are sensitive to the relationship between decision makers, their decisions and consequential level of risk to people. It is essential that great sensitivity be used when expressing reasoning for comparative levels of assessed risk. The exact words to use will depend upon the country and the circumstances of the decision – it is essential to understand the specific legal context. It may be helpful to obtain specialist, jurisdiction specific, legal advice prior to undertaking such activities in order to manage the risk of legal misunderstandings of the risk evaluation methodology and its findings.

5.4. REVIEW OF RISK EVALUATION MERITS

A legal review of decisions requires the review of underlying risk evaluations. For these reasons it is advisable as part of the risk evaluation process to prepare documentation which:

- clearly articulates the strengths and weaknesses of any risk evaluation conducted;
- states that the risk evaluation provides an evaluation of possible future events but is not a guarantee of what will actually occur; offers an opinion as to the appropriate use and limitations of the specific risk evaluation findings.

6. CONCLUSION

The application of risk-based approaches in the process of tunnel safety management is now very common. In several guidelines, standards and regulations the use of risk analysis under certain circumstances has increased in importance in recent years. Often however, there are no specific requirements for how to perform a risk analysis and how to evaluate the resulting risk. Risk-based approaches allow a structured, harmonised and transparent assessment of risks for an individual tunnel, including the consideration of the local risk situation in terms of relevant influence factors, their interrelations and possible consequences of incidents. Moreover, risk-based approaches make it possible to propose relevant additional safety measures to provide risk mitigation and can be the basis for decision-making considering cost-effectiveness to assure the optimum use of limited financial resources. Nevertheless risk-based methods should be used in a conscious manner, recognising their limitations and the domain for their validity. Such methods should be considered an aid to professional judgment and decision making, rather than a substitute. Furthermore, risk analysis should only be performed by experts with sufficient experience and understanding of the methods they use.

Risk evaluation is a very important and sensitive element of the whole risk assessment process. It is intended to answer the question of whether a tunnel is safe enough; i.e. whether the risks identified/quantified in the risk analysis are acceptable or whether additional safety measures are needed to fulfil the safety targets. For this purpose some kind of risk criteria have to be defined which can be used as target values in the evaluation process; the definition of such criteria is a demanding task because it is embedded in a specific legal, social and cultural environment. When a risk analysis is performed, it is important to realise that decision-making about risks is complex. Not only are technical and mathematical aspects important, but ethical, political, societal and other factors have an important role as well. Whereas risk analysis is a scientific process of assessment and/or quantification of probabilities and the expected consequences of identified risks, risk evaluation is a socio-political process in which judgments are made about the acceptability of those risks.

Among these aspects the discussion about the acceptability of risks is strongly influenced by risk perception. Even though risk evaluation always includes aspects of weighting and judgments on acceptability, strategies for risk evaluation can be developed in a structured way considering the relevant influence factors of risk perception etc. Therefore, for the determination of risk evaluation criteria there is no generally applicable *"right"* or *"wrong"* safety target.

The description of the principles of risk evaluation in *chapter 3, page 19* shows that there is a wide spectrum of approaches to the representation of risks and therefore there are also many different strategies for risk evaluation. Experience shows that in practice, combinations of the principles discussed are often applied. Some established practical applications are described in *chapter 4, page 32,* illustrating the variety of practical applications and the range of risk that may be evaluated as acceptable.

From a practical point of view it should be noted that there are several approaches to the implementation of risk evaluation strategies and any comparison of different acceptability criteria that are in use should be done in the context of the scope and methodology of the risk analysis, with careful attention to whether risk is normalised in terms of tunnel length or other parameters.

The following recommendations can be given for the practical use of risk evaluation criteria:

- risk analysis and evaluation is usually just one of a number of bases for decision-making in tunnel safety management;
- when determining risk evaluation criteria it is important to consider that the strategy for risk evaluation is strongly dependent on the method of risk analysis chosen and the specific scope and circumstances of the risk assessment;
- although risk models try to be as close to reality as possible and try to implement realistic base data, it is important to consider that the models can never predict real events and that there is a degree of uncertainty and fuzziness in the results;
- considering the uncertainty, the results of quantitative risk analysis should be considered accurate only to an order of magnitude and should be supported by sensitivity studies or similar;
- risk evaluation by relative comparison (e.g. of an existing state to a reference state of a tunnel) may improve the robustness of conclusions drawn;
- the interpretation of the results of risk analyses requires sufficient experience and understanding of the methods and the evaluation strategies used.

Finally, in *chapter 5, page 54* a short discussion of possible legal implications of risk analysis highlights the topic from a different perspective. In this context, risk evaluation provides a systematic framework for assisting decision makers with complex decisions that impact on human safety and asset protection. Such a systematic approach helps the decision making process and would therefore form part of the evidence in any post-incident legal investigation into the basis of decisions on tunnel safety provisions.

Central to ensuring robust decisions are made is effectively communicating that a risk evaluation:

- is not a substitute for a decision,
- is not a guarantee,
- is a method of supporting decisions which considers the likelihood and consequences of possible events.

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GLOSSARY	
ALARP (As Low As Reasonably Practicable)	A principle used for defining a zone of risk that can be achieved by appropriate risk mitigation measures and that is acceptable It implies e.g. that risk reduction in this area should be performed as long as the costs of risk mitigation measures are not disproportional large in comparison to their risk reduction effects.
Consequence	The outcome of an event in terms of damage to the health of people, to property or to the environment.
Consequence analysis	A systematic procedure to describe and/or calculate consequences.
Cost effectiveness	An approach that considers the efficiency of safety measures compared to their potential for risk reduction.
Emergency exit	Exit that leads to a protected route or safe place.
Evacuation time	Calculated time required for occupants to evacuate from their location in the tunnel to a safe area.
Event	Occurrence or change of a particular set of circumstances.
Event tree	Graphical, bottom-up inductive technique, mapping all possible courses of an initial event, their frequencies and consequences.
Expected value	A typical numerical representation of societal risk as the sum of the frequencies/ probabilities of each event or scenario multiplied by their corresponding consequences.
Fault tree	Graphical, top-down, deductive technique that uses Boolean operators (the most basic of which are NOT, AND, and OR) to evaluate the consequences of a risk by mapping all probable outcomes of a trigger event in their logic sequence.
FN curve	A typical representation of societal risk as a graph with the ordinate representing the cumulative frequency distribution of N or more units of consequence (e.g. fatalities) and the abscissa representing the corresponding consequence.
Frequency	The number of times a specified event occurs within a specified interval (e.g. accidents per year).
GALE (globally at least equivalent)	A principle used for defining a level of risk that can be achieved and requires that a new system must offer an overall level of safety at least equivalent to that offered by systems in operation providing comparable services.
Harm	Physical injury or damage to the health of people, or damage to property or the environment.
Hazard	Potential source of harm
Hazard identification	A process to recognise hazards and define their basic characteristics.
Incident	Abnormal and unplanned event adversely affecting tunnel operations and safety (including accidents)
Individual risk	Risk related to a particular person (usually expressed as a probability to be injured or killed).
Marginal cost	The price one is willing to pay for a marginal increase in safety in terms of saving one unit of damage.

GLOSSARY (CONTINUED)	
Monetary risk	Risk including marginal cost per unit of damage.
Perceived risk	Weighted risk including risk aversion.
Probability	Likelihood that an event may occur, expressed as a number between 0 and 1.
Probability analysis	Systematic procedure for describing and/or calculating the probability of a future event.
"Quantitative Risk Analysis (QRA)"	A risk analysis method based on numerical calculations
Reference tunnel	Tunnel similar to a tunnel to be investigated which is in line with all requirements and fulfils all conditions defined in guidelines and standards.
Residual risk	Risk remaining after protective measures have been implemented.
Risk	Combination of the probability of occurrence of harm and the severity of the harm (ISO IEC 51).
Risk analysis	Systematic use of available information to identify hazard and to estimate the risk (ISO IEC 51).
Risk assessment	Overall process comprising a risk analysis and a risk evaluation (ISO IEC 51).
Risk aversion	Empirical discernible phenomenon that some accidents are perceived to be much worse than their inherent risk would indicate.
Risk criteria	The reference points against which the results of the risk analysis are to be assessed. The criteria are generally based on experience and/or theoretical knowledge used as a basis of the decision on tolerable risk.
Risk estimation	Process of derivation of risk values based upon the probability analysis and the consequence analysis.
Risk evaluation	Procedure based on the risk analysis to determine whether the tolerable risk has been achieved (ISO IEC 51).
Risk management	A systematic process undertaken by an organisation in order to reach and maintain a tolerable level of risk.
Risk perception	The way in which a stakeholder views a risk, based on a set of values or concerns.
Risk reduction	Actions taken to reduce the probability and/or negative consequences associated with a risk.
Safety	Freedom from unacceptable levels of risk (ISO IEC 51).
Safety analysis	Systematic use of available information to identify hazards and to estimate the safety level.
Safety assessment	Overall process comprising a safety analysis and a safety evaluation
Safety evaluation	Procedure based on the safety analysis to determine whether the freedom from unacceptable risk has been achieved.
Safety management	Systematic process undertaken by the management organization of a tunnel in order to attain and maintain a compliant level of safety.

GLOSSARY (CONTINUED)	
Scenario analysis	The analysis of the consequences of a wide range of accidents that may occur in a tunnel.
Scenario based risk approach	Family of methods for risk assessment usually based on a deterministic analysis of the resulting consequences of a set of representative scenarios under defined conditions. A procedure for selection of scenarios to be analyzed is included also. The risk assessment is done separately for each single scenario on the basis of its characteristic indicators.
Societal risk	Risk relevant to society, usually expressed as an expected number of fatalities or by an FN curve.
System based risk approach	Family of methods for risk assessment, in which risk values for an overall system are estimated considering all relevant events/scenarios which can affect persons in the system considered. The risk assessment is done for the whole tunnel system investigated on the basis of the risk values of the system.
Traffic accident	Incident involving vehicle collision.
Tolerable risk	Risk which is accepted in a given context based on the current values of society (ISO IEC 51)
Tunnel system	The whole of the structure, installations, internal and external infrastructure, operation and management organization of a tunnel.

1. CURRENT PRACTICE OF RISK ANALYSIS FOR ROAD TUNNELS

On the following pages, a short description of 8 practical methodologies, their characteristics, results and associated strategy of risk evaluation are presented. Special emphasis is put on information about the range and limits of application, to advise the reader on the types of problems that the respective methodology is suited to. Finally, the suitability of the methodology to meet the specific requirements of EU Directive 2004/54/EC is discussed.

The methodologies presented are listed below (in alphabetic order):

- Austrian tunnel risk model TuRisMo,
- Czech risk analysis for road tunnels,
- Dutch scenario analysis for road tunnels,
- Dutch TUNPRIM model,
- French specific hazard investigation,
- German risk analysis for road tunnels,
- Italian Risk Analysis Method (IRAM),
- OECD/PIARC DG-QRAM model.

Six of these methods were already included in the PIARC report *"Risk Analysis for Road Tunnels"*. The description of these methods was revised and updated according to new developments. Two recently developed methods were added, the Czech risk analysis, and the German risk analysis.

1.1. AUSTRIAN TUNNEL RISK MODEL TURISMO

General

In Austria several risk analysis methods are applied for road tunnels:

- The standard method is the Austrian Tunnel Risk Model TuRisMo – published in the guideline RVS 09.03.11 in 2008 [21];
- on the basis of this method a simplified approach was developed, which may be used for simple cases [22];
- the risk of dangerous goods transports through road tunnel is assessed applying the risk model DG-QRAM (chapter 2.1);
- for specific problems scenario-based approaches are used, the selection of the method applied depends on the problem to be investigated – there are no recommendations for a specific method.

Approach adopted

For the Austrian Tunnel Risk Model, a set of different methodical components is used to analyse the whole system of safety-related influencing factors.

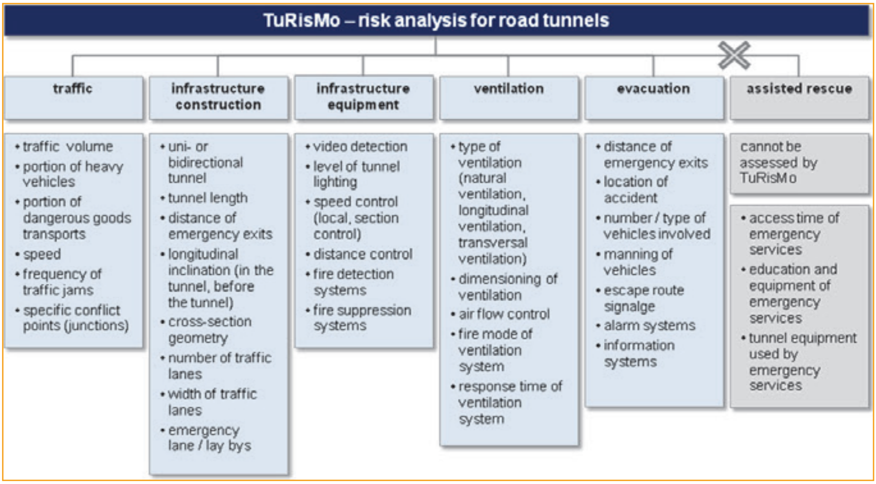

FIGURE 27 – RISK INFLUENCING FACTORS INCLUDED IN THE AUSTRIAN TUNNEL RISK MODEL TURISMO

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 (tunnel accidents rates) and the distribution (relative frequencies) across the branches of the event tree.

- Quantitative consequence analysis
  - statistical approach to quantify the consequences of the physical effects of tunnel accidents;
  - combination of a model of smoke spread in the tunnel with an evacuation model (simulation of self-rescue of people in the tunnel) to quantify the consequences of fires.

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 Austrian tunnel risk model TuRisMo was published in the Austrian guideline RVS 09.03.11 in June 2008. The guideline is also available in English language.

Results of risk analysis and strategy of risk evaluation

The risk model only covers the risk of tunnel users. The result of risk analysis is the expected value of the societal risk for the tunnel investigated. The respective shares of risk are shown separately for:

- mechanical effects,
- fires,
- dangerous goods.

Two different strategies are applied for risk evaluation:

- **expected value – applied as relative risk criteria**
  The risk of the tunnel investigated is compared to the risk of a reference tunnel. As a reference case, a tunnel of the same length, type and traffic characteristics fully complying with the minimum safety requirements as per the EU Directive is used. The divergences identified can be assessed in terms of risk. If the risk of the tunnel investigated exceeds the risk of the reference tunnel, additional safety measures have to be evaluated to offset the divergences. The assessment of the safety measures can be completed by a cost-effectiveness analysis ;

- **expected value – applied as absolute risk criteria**
  The absolute magnitude of the expected value of the tunnel investigated is used to classify the tunnel into one of four danger classes according to the following classification scheme of guidelines RVS 09.02.31 (*figure 28*). The danger class is used as a criterion to define the standards for tunnel equipment according to the Austrian tunnel design guidelines RVS.

RISK (EXPECTED VALUE)		DANGER CLASS
LOWER LIMIT	UPPER LIMIT	
-	$< 2 \cdot 10^{-2}$	I
$> 2 \cdot 10^{-2}$	$< 1 \cdot 10^{-1}$	II
$> 1 \cdot 10^{-1}$	$< 5 \cdot 10^{-1}$	III
$> 5 \cdot 10^{-1}$	-	IV

FIGURE 28 – DEFINITION OF DANGER CLASSES FOR ROAD TUNNELS – ACCORDING TO GUIDELINES RVS 09.02.31 [22]

Range and limits of application

The model was developed on the basis of the EU Directive and therefore also covers all fields of application defined in the Directive, except for dangerous goods transport (for this specific application the risk model DG-QRAM is used in Austria). The model can be used for a wide range of applications, such as safety assessment of new or existing tunnels, support of the 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 covers all types of road tunnels with longitudinal or transverse ventilation, and all types of tunnel accidents with injuries (vehicle breakdowns with fire; vehicle accidents, vehicle accidents with fire).

The Austrian tunnel risk model is a standardised tool for a wide range of different tunnel types. Specific values can be taken out of tables published in the guidelines. These values were developed by:

- evaluating 450 tunnel accidents in terms of frequencies and consequences,
- systematically applying the smoke spread model and the evacuation model for typical tunnel situations (for fire scenarios).

These values can be used for many tunnels without further detailed modelling. For specific cases which are beyond the limits of application defined in the guideline, the model can be applied as well, however the input data for the fire scenarios have to be calculated by applying the smoke spread model and the evacuation model to the specific tunnel situation.

The advantages of the model are:

- a simple execution for those tunnels which do not require detailed modelling;
- the high flexibility of the constituent methods, so that it is applicable to almost every tunnel, ventilation or traffic configuration;
- its capability to include the effects of almost every important safety-related 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 event of a fire. This allows the investigation of all influences on the timescales of this process;
- its simple, clearly understandable and easily comparable results.

However, the results of the model (expected values) do not include information about the distribution of different accident consequence classes (such as FN curves, a graph of the frequency of the occurrence of accidents with N or more fatalities). Therefore the model is not suited specifically to 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 dangerous goods.

1.2. CZECH RISK ANALYSIS FOR ROAD TUNNELS

Approach adopted

The requirements on the equipment and the operation of road tunnels are mandatory according to a set of technical standards published by Ministry of transport. The standard TP98 *"Technological equipment of the road tunnels"* describes all essential conditions and procedures to design traffic–, technological– and safety systems in an optimal way. The procedures for operation and maintenance are formulated in the TP154 *"Operation, management and maintenance of the road tunnels"*.

The safety policies and qualitative and quantitative methods of risk analysis are elaborated in the new standard TP *"Safety in the road tunnels"* (this standard is to be published in the first half of 2010). For the investigation of issues of dangerous goods transport the OECD/PIARC DG QRA model is recommended to be used. The scenario analysis as a standardized deterministic method named CAPITA is formulated in this standard too.

The method is based on determining of possible week spots in the tunnel system design. Only those subsystems not prescribed compulsory by standards are taken in account. The majority of subsystems in the tunnel are designed by well-defined procedures. For example, the lighting system is computed by analytical forms, the function of ventilation is even simulated by different boundary conditions, etc. Another group of subsystems offer considerably bigger degree of freedom in theirs design; typically, covering tunnel by smoke detection, positioning of loudspeakers and information displays, etc. The method of risk analysis proposed in the standard is able to estimate an effect to a safety given by these concrete subsystems.

The proposed method evaluates the time of a self-rescue process given by three time segments: awareness time reaction time and evacuation (movement) time. Whilst time of evacuation is given by the distance to the exits and could be partially influenced by quality of escape footpaths, the other two time segments can be shorten by a good system of event identification and a good information system. The proposed method quantifies the quality of mentioned subsystems in relation to the possibilities to escape a tunnel. Only a fire case is investigated because an escape plays significant role in this case.

The frequency and consequences of tunnel accidents are obtained through evaluation of only 12 tunnels and 200 accidents in the years 2004-2009. Based on statistical evaluation of all accidents, there is on average 0.312 accidents per veh.-km. This value is approximately three times higher as shows the same parameter published in Austria for 447 accidents. The five small fires have been identified. It is possible to estimate very roughly the frequency of fires as the number $7.7973.10^{-3}$ fires per veh.-km. Generally said, there is not enough statistical data and therefore it is not recommended to use the fault tree analysis.

The CAPITA method is based on the following steps:

- positioning and type of cars in a tube when a fire starts is given by micro-simulation model (for example VISSIM or AIMSUN), the output is the number of people in the tunnel. The realistic traffic flow parameters are input parameters to the simulation;
- selection of fire scenario (5 MW, 15 MW, 30 MW);
- estimation of basic escape time by combination of fuzzy logic and micro-simulation escape model for people (e.g. SIMULEX);
- estimation of awareness and reaction time based on assessment of the system of an automated fire identification and system for tunnel users information;
- comparison of calculated escape time to a smoke spread in a tunnel (physical model), which gives a number of estimated mortalities.

Subsystems and factors influencing the escape possibilities creating evacuation model are depicted in the *figure 29*. Because of heterogeneous parameters the expert system shall be used for an assessment of the particular time segments.

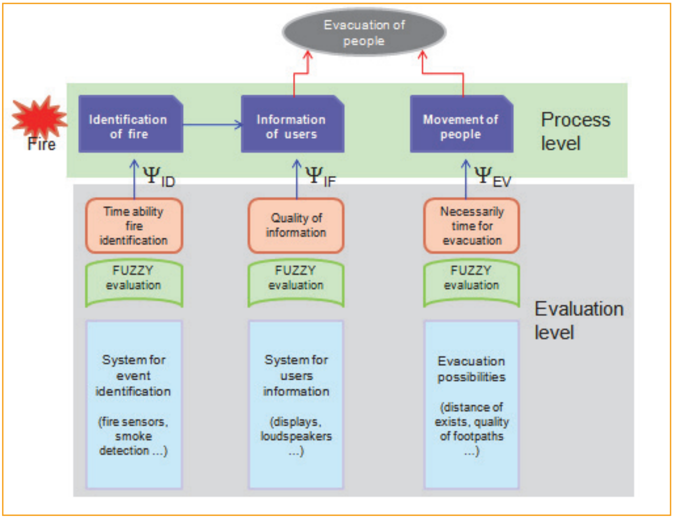

FIGURE 29 – EVACUATION INFLUENCING FACTORS EVALUATED BY CZECH RISK ANALYSIS MODEL

Well defined and controllable expert rules form a basis of fuzzy linguistic rules system. The estimated time needed for identification of fire is the first output. An identification system is created by fibre sensor, smoke and pollutions detection and automated processing system. Input parameters are, for example, position of detectors, covering of tunnel by smoke-detection cameras etc. Similarly, expert rules are used for assessment of information system (second time segment) and for estimating of the realistic evacuation time (third time segment). The resulting summary time shows a chance of tunnel users to escape the tunnel.

Result of risk analysis and strategy of risk evaluation

The proposed method gives a possibility to evaluate a contribution of decisive tunnel systems to decrease the mortalities of tunnel users. Systems for automated fire identification, information of users and escape system are evaluated from the time point of view. Because of heterogeneity, well controllable fuzzy linguistic rule system is applied. To decrease uncertainty of an analysis the micro-simulations for determining of car positions within a tunnel and for users escape are used. The scenario deterministic analysis is used and the results are:

- numerical evaluation how contributes single system to the self-rescue process;
- detailed multi-parametrical assessment of each system enabling to investigate a sensitivity to single parameter;
- estimation of mortalities for given scenario;
- feedback improvement of systems parameters to increase chance to escape for tunnel users.

Range and limits of applications

The frequency of a scenario does not affect this kind of analysis. The consequences of a fire in a tunnel are evaluated only.

The proposed method provides a unique way to investigate detailed parameters of tunnel decisive systems and theirs contribution to the tunnel safety. This method is well controllable and understandable by stakeholders. The accuracy of time escape evaluation has been significantly increased due to involvement of larger expert group by forming of the rules.

1.3. DUTCH SCENARIO ANALYSIS FOR ROAD TUNNELS

General

Since 2006 both the RWS-QRA-model and the scenario analysis method are made obligatory by law.
They can both be found on the website:
http://www.rws.nl/kenniscentrum/veiligheid/steunpunt%5Ftunnelveiligheid/veiligheidsbeschouwingen

Approach adopted

The scenario analysis is a standardised, deterministic method that can be used to identify possible weak spots in the tunnel system as a whole (especially the infrastructure 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 (infrastructure 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:

- selection of the analysis team;
- definition of safety criteria (criteria for prevention, mitigation, self-rescue and emergency response; in practice it is very difficult to define a set of suitable criteria);
- description of the tunnel system;
- selection of relevant scenarios;
- analysis of effects and consequences;
- evaluation of the results, a recommendation for optimisation of the design and a description of the residual risk.

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

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

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

Results of risk analysis and strategy of risk evaluation
The result of the scenario analysis is:

- a description of a number of scenarios in a qualitative and quantitative way;
- an evaluation against acceptance criteria;
- conclusions;
- recommendations for improvement.

Range and limits of application
In practice it turned out to be very difficult to define a set of SMART safety criteria. The emphasis of the method is on the consequences of the selected scenarios. The frequency of a scenario does not play a role as such in the analysis, although the selected scenario has to be *'imaginable'*. The frequency of the scenario does play a

role in the decision on additional safety measures. Additional safety measures, which may be expensive, are not implemented when they only have an effect on scenarios with a low probability.

The description of scenario developments is a good communication tool. It makes the scenario developments understandable and gives insight into the effects of safety measures.

As the risk (frequency x consequences) is not calculated, the cost-effectiveness of measures cannot be assessed quantitatively.

1.4. RWS-QRA MODEL

General

Since 2006 both the RWS-QRA-model and the scenario analysis method are made obligatory by law.
They can both be found on the website:
http://www.rws.nl/kenniscentrum/veiligheid/steunpunt%5Ftunnelveiligheid/veiligheidsbeschouwingen

Approach adopted

The RWS-QRA model is an updated version of the TunPrim spreadsheet model (system-based approach) for a quantitative risk analysis. The model is designed to calculate the internal risk in tunnel tube with uni-directional traffic and with (or without) longitudinal ventilation.

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

Data analyses (statistical approach) are used to quantify the frequencies of initial events (accident rates and fire rates). An event tree analysis (analytical approach) is used to calculate the frequency of the scenarios.

Consequences for each branch of the event tree are calculated as the 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 per person-kilometre) is derived from the Expected Value, the length of the tunnel, the annual number of vehicles and the average occupancy in a vehicle;
- societal risk (FN curves).

In the Netherlands risk acceptance criteria have been defined for tunnel users: an individual risk of $1{,}0 \cdot 10^{-7}$ per person-kilometre and a societal risk of $1{,}0 \cdot 10^{-1}/N^2$ per km per year.

Range and limits of application

The model can be used:

- to compare alternatives;
- to calculate the influence (risk reduction) of (additional) measures;
- to assess the safety level of new or existing tunnels (comparison with the acceptance criteria);
- to support the decision making process for the selection of safety measures;
- to support the decision making process for the routing of dangerous goods.

The model covers all traffic-related types of accidents. Other types of incidents, such as flooding and earthquakes, are not covered in the model.

1.5. FRANCE – SPECIFIC HAZARD INVESTIGATION

General

As part of the safety documentation, in France a specific hazard investigation is performed for every tunnel longer than 300m. Those studies represent risk analysis conforming to the provisions of Article 13 of the EU Directive.

A booklet, part of *"Guide to Road Tunnel Safety Documentation"* is dedicated to Specific Hazard Investigations (booklet 4), so as to provide guidance on the methods for those studies.

Approach adopted

The Specific Hazard Investigation 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-Consequence matrix:

	I Minor or None	II Significant	III Critical	IV Catastrophic	V Major Catastrophe
A Very frequent					
B Frequent					
C Occasional					
D Rare					
E Very rare					
F Extremely rare					

FIGURE 30 – STANDARDIZED FREQUENCY-CONSEQUENCE MATRIX

- a quantitative consequence analysis (smoke movement, user behaviour, 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 and strategy of risk evaluation

The main results of the specific hazard investigation 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 that do not comply with the French 2000-63 technical instruction and/or the EU Directive, an assessment of the level of safety is performed aiming to evaluate whether deviations from standards are acceptable or not regarding safety;

- the scope of measures intended to reduce both the frequency of occurrence and the consequences of accidents is listed;
- assessment of adequacy of measures taken to reduce the consequences of equipment failures, and verification of the absence of a common failure mode for equipment designed to ensure safety;
- where applicable, proposals for improving the provisions are identified.

Those conclusions are focused on safety of road users and their ability to rescue themselves with the help of tunnel equipment and operation of procedures.

Range and limits of application

The method is used for a wide range of different tunnels, from tunnels under design 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;
- to 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, as a result of the standardised 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 comparison of risk levels from one tunnel to another;
- its capability 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 tube 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, such as explosives and LPG (Liquefied Petroleum Gases).

1.6. GERMAN RISK ANALYSIS FOR ROAD TUNNELS

General

The minimum requirements on the equipment and the operation of road tunnels are specified in the guidelines RABT 2006 [22] and 2004/54/EC [2]. In the case of deviations from these requirements, or where a tunnel has special characteristics, a risk analysis shall be carried out to clarify whether additional safety measures and/or supplementary equipment is necessary to ensure a comparable high level of tunnel safety.

In order to specify the requirements according to RABT 2006 and 2004/54/EC and to promote a practical use of risk analyses, a quantitative methodology for the assessment of road tunnel safety was developed [28].

Approach adopted

The German risk analysis for road tunnels allows a standardised and comparable implementation of safety assessments:

- if a tunnel does not comply with the valid specifications with regard to design, safety measures or other aspects, the resulting risks are determined, using an event-tree analysis of the two scenario types *"Collision (without fire)"* and *"Fire without hazardous goods according to ADR"* as follows:

a. determine the risk situation for the tunnel to be investigated (initial state);
b. determine the risk situation for the tunnel to be investigated, assuming that all specifications have been adhered to (reference state);
c. if required as a result of the risks for a) and b), the risks for the tunnel to be investigated are determined assuming alternative safety measures;

- the risks for each tunnel section are separately determined and aggregated to a total evaluation to ensure high flexibility of the method with regard to its application to different tunnel types. This way, specific differences between individual tunnel sections, for example different tunnel geometry, can be taken into account;
- the risks for the two scenario types mentioned above are separately determined. This approach shows the importance of the different scenario types with regard to the resulting total risk and the impact of specific safety measures on each scenario type;
- the scenario types are delimited by always considering the most relevant scenario type (worst case), e.g. a fire that results from a collision (or breakdown) is allocated to the scenario type *"Fire"* and not the scenario type *"Collision"*. This is particularly relevant for estimating initial frequencies. It ensures that scenarios

that do not cause significant damage but might lead to damage due to possible, consecutive events are also considered in the safety evaluation;
- the risk indicator *"fatalities"* is used for determining damage to persons, as is common in comparable risk studies. Damage to goods is quantified in Euro. The *"Damage to goods"* also includes the consequential costs for injured persons under the consequential costs of accidents. The method provides additional options for combining the two risk indicators by using a comparable, monetary basis;
- the use of safety measures as part of the safety evaluation focuses on constructive and technical measures (in particular escape routes and ventilation systems). However, the method suggested can also be used to consider organisational and operational measures.

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

Results of risk analysis and strategy of risk evaluation

It is suggested to use an absolute evaluation criterion in the form of acceptability ranges in the damage frequency diagram in order to comply with the requirements in the directives RABT 2006 and 2004/54/EG for risk evaluation of tunnels with *"special characteristics"* and to ensure a standardised safety level. The safety measures requested in the directive have the primary purpose of reducing risks to persons. The evaluation in the damage frequency diagram is therefore exclusively performed for the risk indicator "Fatalities". The following procedure is suggested for evaluating risks by using the damage frequency diagram:

1. for the tunnel to be investigated, the frequencies and extents of damage with regard to the risk indicator *"Fatalities"* are determined for the respective sub-scenarios of the two event types *"Collision (without fire)"* and *"Fire without hazardous goods according to the ADR"* using event trees. The frequencies are standardised for a tunnel length of 1 km and one year to generate a standardised reference value. For the cost-effectiveness ratio, risk aversion is not considered by including a risk aversion factor in the calculation, but implicitly, through the incline of the acceptability line.
2. for the tunnel to be investigated, the resulting cumulative curve (resulting from the respective scenarios for the segments belonging to the tunnel) is standardised for a reference length of 1 km and entered in the damage frequency diagram.
3. if the standardised, cumulative curve is not in the range of the acceptable risks, additional safety measures have to be provided. The cumulative curve for the tunnel under investigation must then be re-determined, taking possible, additional/

alternative measures into account, and re-evaluated with regard to its relative position to the acceptability line. If the newly determined cumulative curve is still not within the acceptable area of the damage frequency diagram, additional measures must be investigated or implemented.

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

The requirements of the directives RABT 2006 and. 2004/54/EG must be adhered to. If the regulatory requirements according to the directives cannot be implemented for a specific tunnel appropriate alternative safety measures have to be provided. The procedure of evaluation is described in *chapter 4.5, page 49*.

Range and limits of application

The risk model can be applied both to new tunnels and existing tunnels, in particular for selecting the proper additional complementary equipment that the tunnels with special characteristics needs, or the alternative safety measures to be adapted when there is no chance of implementing all the requirements typical of the considered existing tunnels. A major change of risk relevant factors that indicates that the risks for a tunnel have increased might require an update of the risk evaluation. For the categorisation of tunnels for the transport of dangerous goods another approach is developed.

1.7. ITALIAN RISK ANALYSIS METHOD FOR ROAD TUNNELS (IRAM)

General

The Italian Decree 264/06 identifies, according to the recommendations of the EU Directive 2004/54/EC, a methodology of risk analysis and the risk evaluation criteria for the tunnels of the Trans European Road Network located on the Italian road network. Risk analysis must be carried out for all tunnels located on the Italian road network. Specifically, the risk analysis must be performed for all tunnels with anomalies in the safety parameters (tunnels with special characteristics) and for all tunnels that are not compliant with the minimum safety requirements identified by the Directive and the Decree (tunnels with deficit). The main objective of the risk analysis is to demonstrate the effectiveness of the alternative and integrative safety measures in order to satisfy the safety objectives quantified in terms of social risk pertaining to a tunnel.

ANAS, the Italian government-owned motorway company in its *"Guidelines for Safety Design of Road Tunnels"* [20] published a specific probabilistic risk analysis method for the risk assessment of road tunnels, called Italian Risk Analysis Method (IRAM).

Approach adopted

IRAM according to the systemic approach defines a tunnel as a complex formed by structural elements, surrounding environment, traffic, safety systems and equipment, management procedures [23].

Road accident events related to the geometric characteristics of the infrastructure which are not induced by the specific environment of the tunnel and which do not involve additional risks for users above those normally associated with road traffic circulation are not included in the risk analysis being considered by other regulations.

IRAM includes and goes beyond the scenario analysis and the fire safety engineering approaches.

IRAM adopts an actuarial risk model ($R=f \otimes N + \sigma (R)$). The occurring frequencies for critical events fixed by law, i.e. fires, collisions with fire, spillages of flammable substances, releases of toxic and noxious substances, are represented by probability density functions determined from available real data treated according to the Bayesian approach; the consequences on exposed population, defined as the set of tunnel users and safety addicts, are represented by means of probability density functions, determined from the solution of the statistical hazard flow and evacuation process models. The evacuation model takes into account the queue formation in the tunnel in order to quantify the exposed population. The statistical treatment of hazard flow and evacuation processes takes into account the uncertainties related to the models as well as to the safety systems performance.

IRAM adopts the event tree technique only to represent the statistical evolution of hazard flow as conditioned by the performance of the safety systems. The transition probabilities between different branches of the event tree are evaluated starting from probability distribution functions determined according to the Bayesian network theory. The event tree technique in the IRAM is not used to calculate the social risk of a tunnel as currently practiced in the framework of the simplified approaches to the risk analysis of the transport systems.

IRAM makes it possible to determine the self-rescue of users in possible evacuation scenarios and to quantify the risk pertaining to each tunnel over a fixed time period.

IRAM allows the demonstration of the effectiveness of the total set of prevention, protection, mitigation and management measures in fulfilling the safety objectives fixed by the EU Directive, thus ensuring that the risk related to the tunnel, represented in terms of Complementary Cumulated Curves (social risk indicators) lies below the limit of tolerable risk. According to the ALARP (As Low As Reasonably Practicable) criterion it must be demonstrated that the risk related to the tunnel can not be further decreased due to disproportionate costs (cost-safety analysis).

All the peculiarities of the IRAM are detailed in the bibliography.

IRAM main features

According to the recommendations of the EU Directive 2004/54/EC and the prescriptions of the Italian Decree 264/06 IRAM considers the tunnel interacting with the surrounding environment and takes into account:

- architectural and structural characteristics of the tunnel;
- traffic characteristics such as volume, composition, flow;
- rates of occurrence of critical events surveyed or projected;
- reliability and efficiency of installed tunnel safety systems.

The statistical set of critical events is characterised in terms of probability of occurrence deriving from real available data or from data pertaining to the specific analysed tunnel if available.

The safety systems that determine the response of the tunnel system to emergency conditions and define the dangerous conditions for the population exposed to hazard flow resulting from possible critical events are characterized in terms of performance complying with the best current available technologies.

The event tree technique is characterized in terms of probability of occurrence of critical events and their probable evolution along specific individual branches as determined by the action of safety systems quantified in terms of their intrinsic reliability and efficiency. The event tree is adopted as a representation technique only and not as a simplified tool to perform risk calculations.

The self-rescue of the users in a specific tunnel is determined by quantifying and zoning the hazard flow inside the structure. The various zones in the hazard flow identify the conditions in which the user escape process takes place.

The hazard flow is determined by modelling its evolution as conditioned by the containment action of the safety systems on the chemical and physical phenomena generated by the occurrence of critical events.

The hazard flow is modelled as a statistical process at various levels of detail using the best known available techniques (Analytical, 1D-3D numerical models).

Hazard flow modelling provides the input data for the simulation of the user escape process in different evacuation scenarios.

The number of people involved in the evacuation process is determined by the formulation and solution of suitable models of the formation of vehicle tail-backs in the tunnel under analysis. The evacuation capabilities and health conditions of the exposed population are characterised by means of suitable probability distribution functions, keeping into account age, mobility capabilities, gender, sex, etc.

According to the prescriptions of the Italian Decree 264/06 a social risk measure defined as the number of fatalities per year resulting from a set of possible evacuation scenarios consequent to the occurrence of a set of critical events is adopted as risk indicator for a tunnel.

The social risk for a tunnel is represented by the complementary cumulative curve (C.C.C.) which contains all available information concerning the occurrence frequencies of a set of significant accident events and the consequences deriving from possible evacuation scenarios, and represents the risk in the form of a complete distribution of potential losses keeping into account the effects of uncertainties related to the simulation models and the performance of the adopted safety systems.

A risk indicator useful in engineering practice is the Expected Risk Value, the first moment of the complementary cumulative curve, coinciding with the area underlying the complementary cumulative curve.

Results of risk analysis and risk evaluation

According to the prescriptions of the Italian Decree 264/06 the ALARP principle is adopted to fix specific levels of acceptability and non-acceptability of risk. The tolerable and acceptable risk levels are represented by straight lines on the F-N diagram with predefined intercepts and slopes fixed by law.

The portion of the F-N diagram limited by the lines of acceptability and non-acceptability of risk identifies the area of application of the ALARP criterion

The ALARP criterion requires the determination of the design solution that assures the greatest reduction in the risk level of a given tunnel and that it is compatible with the technical and economic constraints of the project.

The zone of the diagram with consequences less or equal to two is not to be considered because it is pertaining to the road safety.

The *figure 31, following page,* shows the FN diagram as reported in the Decree.

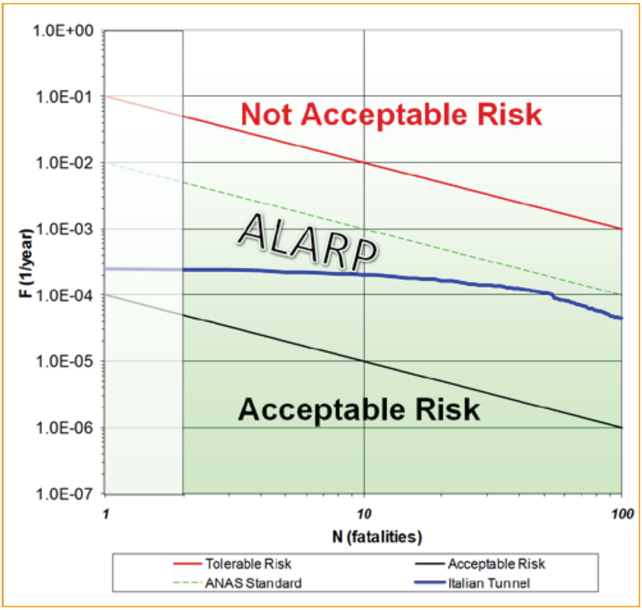

FIGURE 31 – EXAMPLE OF FN-DIAGRAM WITH RISK ACCEPTANCE LINES

The procedure for assessing the level of risk for a tunnel involves:

- verifying that the complementary cumulative curve associated with the tunnel lays below the unacceptable risk limit line (tolerability limit);
- comparing the areas underlying different complementary cumulated curves corresponding to different tunnel safety designs;
- taking decisions according to cost-safety criteria.

If the complementary cumulative curve for the tunnel falls within the area of non-acceptability, safety measures must be implemented to bring the curve below the tolerance limit regardless of the costs involved. If the curve falls within the area of conditional acceptability (ALARP area), safety measures must be implemented as compatible with the cost-safety criteria. If the curve falls within the area of acceptability, no further safety measures need to be implemented.

The cost-safety criteria are used to decide between alternative design solutions comparing the expected risk values and the related implementation costs.

The expected risk value can be used to determine the conditions of equivalence between different design solutions for a tunnel when the associated complementary cumulative curves fall within the ALARP area (comparative criterion).

Range and limits of application

IRAM can be applied both to existing tunnels and new tunnels. It allows the selection of the proper additional complementary equipment that the tunnel needs, or the alternative safety measures to be adopted when it is not possible to implement all the minimal requirements related to the examined tunnel.

No special limitations for the application of the IRAM are stated. Specifically, IRAM is compliant with the ADR prescriptions and allows the evaluation of the social risk of a tunnel in which dangerous goods transport is authorised.

Any approach based on deterministic scenario analysis or any risk assessment based on a limited number of critical events are not compliant with the Italian regulations which require the societal risk of a tunnel to be determined on a probabilistic set of evacuation scenarios resulting from a probabilistic set of critical events.

2. PRACTICAL METHOD SPECIFICALLY APPLICABLE FOR TRANSPORT OF DANGEROUS GOODS

General

The OECD/PIARC risk model is widely used in many countries. In the course of the implementation of ADR tunnel regulations, various countries developed different risk evaluation procedures for the transport of dangerous goods through road tunnels, fully or partly based on the results of DG-QRAM. Hence this chapter is divided into two parts: in the first part of this chapter the method of the risk model DG-QRAM is presented; the second part focuses on the application of the model in different countries.

Overview of the OECD/PIARC DG-QRA model

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 that an accident has happened. A table has been established, and included in the model, that includes quantitative figures for each scenario, which distinguishes between different boundary conditions (tunnel/open air routes, urban/rural areas);
  - accident rates on tunnel/open air routes are defined by the user, on the basis of national statistics (default values, or those generally used for the tunnels project), or local statistics (observation of accidents for in-service roads/tunnels).

- Quantitative consequence analysis:

  – A 2D and a simpler 1D tool, based on pre-determined calculations of physical consequences in the open (for a range of meteorological conditions), have been implemented in the DG QRA model. The model can calculate the consequences (in terms of fatalities and/or injuries) for road users and local population in the vicinity of the roads, for a set of scenarios representative of the observed dangerous goods traffic;
  – a separate 1D tool has been incorporated to calculate the physical and physiological consequences of scenarios in tunnels;

The combination of quantitative frequency and consequence analyses allows the calculation of FN curves.

The DG QRA model is based upon the following set of 13 representative scenarios.

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

FIGURE 32 – DANGEROUS GOODS QRAM MODEL SCENARIOS

Figure 32, scenarios 3 to 13 are specifically related to dangerous goods transport, which is not the case for scenarios 1 and 2 (truck fires), which were included in the model for benchmarking purposes only. Indeed, the OECD/PIARC QRA model is specifically dedicated to risk assessment of transport of dangerous goods through road tunnels and should not be used for other purposes, for which the model has not been elaborated for. The scenarios implemented in the model represent the main effects of dangerous goods 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 range of dangerous goods traffic, most of the goods can be represented by this set of scenarios.

Results of risk analysis and strategy of risk evaluation
The OECD/PIARC DG-QRA model is capable of calculating:

- expected risk value (EV) & FN curves (societal risk),
- individual risk figures.

The considered consequences may be fatalities only or fatalities + injuries towards road users and/or local population.

However, the model is much more often used to calculate societal risk figures (EV and/or FN curves) than individual risk figures.

It is often used in two steps. In a first step, an expected risk value (societal risk) 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 cumulative expected value can be calculated. For that purpose, the following data are needed:

- dangerous goods traffic volume and composition;
- overall traffic volume, composition (cars, HGV, coaches/busses), and daily/seasonal variations;
- accident rates along the routes;
- tunnel characteristics (length, longitudinal and cross sectional geometry, ventilation, drainage system, emergency exits, etc.).

The data used may refer to the situation a number of years after a tunnel is put into operation (for tunnels under design or tunnels at the commissioning stage), or a number of 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 the DG QRA model can be used, in a second step:

- for comparison of risks of tunnel route and possible alternative routes;
- for comparison of various options for dangerous goods transport limitations (e.g. according to the ADR categorisation regime);
- for comparison of calculated risks with acceptance criteria.

For this second step, the following supplementary data may be needed, if relevant: data collection for the selected alternative routes, with an homogeneous level of detail for every compared route.

In order to illustrate the use of the OECD/PIARC DG-QRA model in practice, some examples of practical applications in different countries are presented.

Range and limits of application

The model is well suited to take decisions regarding dangerous goods traffic authorisation in a tunnel.

The model is not suitable for a general risk analysis for road tunnels.

2.1. AUSTRIA

In Austria a multistage risk assessment process is applied which is defined in the guideline RVS 09.03.12 [18]:

a. simplified approach - applying a classification matrix;
b. risk analysis for a tunnel – applying DG-QRAM;
c. investigation of additional risk mitigation measures – on the basis of the DG-QRAM results;
d. investigation of alternative transport routes for dangerous goods – applying DG-QRAM.

The process starts out with a simplified assessment (stage a). It shall permit a simple identification of tunnels with a low dangerous goods transport risk, considering the type of tunnel (bidirectional or unidirectional traffic), the ventilation system, the traffic volume, the fraction of heavy goods vehicles and a fraction of dangerous goods transports of 3% (representative value for Austria). For the elaboration of the classification matrix, systematic risk calculations were performed for a set of selected reference tunnels using DG-QRAM. As decision criteria an expected risk value of EV = 1 x 10-3 fatalities/year was applied. The classification matrix can be applied without any further risk calculations.

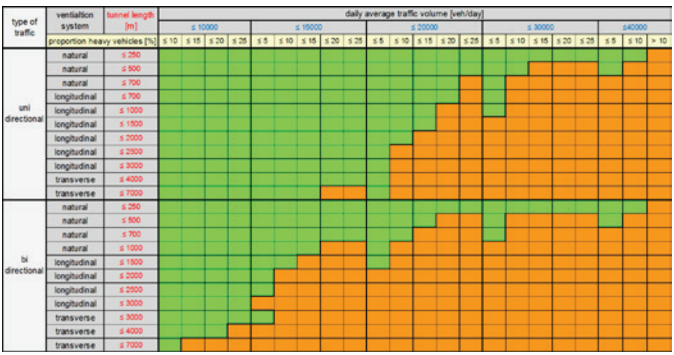

FIGURE 33 – AUSTRIAN CLASSIFICATION MATRIX FOR THE SIMPLIFIED APPROACH ACCORDING TO RVS 09.03.12

If a tunnel is assigned to an orange field of the matrix, a tunnel specific risk analysis has to be performed (stage b), applying DQ-QRAM. For risk evaluation, a reference curve in the F-N diagram is used as absolute evaluation criteria (*chapter 4.3, page 39*).

If the reference curve is exceeded, the risk is evaluated as not acceptable and the tunnel cannot be classified as category A any more. Hence, additional risk mitigation measures have to be implemented (stage c) or alternative transport routes have to be investigated (Stage d). On the basis of the results the tunnel then can be classified according to ADR tunnel categories.

2.2. GERMANY

Similarly to other countries, a multistage risk assessment process was developed for the implementation of the requirements according to ADR. With respect to the needs of the European Directive 2004/54/EG [2] and the German guideline RABT 2006 [26] the specific process was developed within a research project under the leadership of the Federal Highway Research Institute [19].

The developed multistage procedure allows a standardised evaluation of the risks of hazardous goods for all road tunnels on basis of risk analyses and the identification of possible restrictions for dangerous goods transports based on the defined ADR tunnel categories. It comprises the following steps (each divided into two stages):

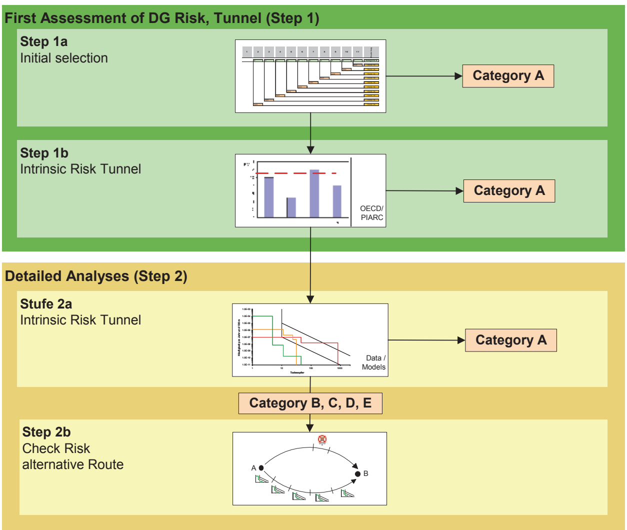

FIGURE 34 – GERMAN MULTISTAGE RISK ASSESSMENT PROCESS

Step 1a) Simplified analysis of risk relevant tunnel characteristics (initial selection of tunnels to be investigated);
Step 1b) Analysis of intrinsic tunnel risk applying DG-QRAM;
Step 2a) Detailed risk analysis for the tunnel applying specific consequence models (e.g. CFD);
Step 2b) Detailed risk analysis for alternative transport routes applying specific consequence models for open routes.

In the first stage of the procedure a rough assessment takes place, followed by in-depth analysis in the second stage. If the tunnel to be assessed cannot be allocated to category A (no restriction) in stage a), stage b) follows. Here, the dangerous goods risk to the tunnel is determined by means of in-depth analysis procedures and more exactly collected object specific input data. If the tunnel can also not be allocated to category A in this stage, the dangerous goods risk is determined not only for the tunnel but also for a suitable alternative route in a further stage.

As a result of the final step, a decision basis becomes available to the authority responsible for the categorisation of the tunnel: B, C, D or E. This includes an assessment of the dangerous goods risks, which arise from the relocation of the transport of dangerous goods to the alternative route.

2.3. SWITZERLAND

In Switzerland, a specific methodology for the categorisation of road tunnels according to the requirements of ADR has been developed with respect to the existing national standard Ordinance on Protection against Major Accidents (OMA) which requires among other aspects the assessment and evaluation of risks caused by the transport of dangerous goods on transit roads including tunnels. In particular, the existing risk acceptability criteria of OMA had to be taken into account. Therefore the DG QRA model had to be adjusted.

As in other countries, a multistage risk assessment process was developed comprising the following steps:

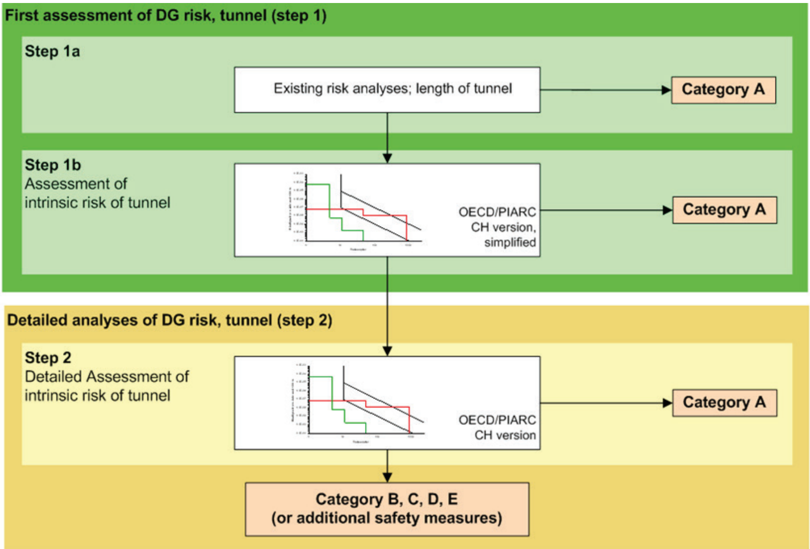

FIGURE 35 – SWISS MULTISTAGE RISK ASSESSMENT PROCESS

1. First assessment:

a. check, if any restrictions and/or detailed analysis are needed tunnels with a length of less than 300 m are regarded as safe and categorised as A-Tunnels; based on the owners report and/or on other analyses concerning the safety level of a tunnel the responsible authority decides whether a further risk analysis is needed or the tunnel can be categorised as an A-Tunnel;
b. analysis of tunnel risk applying adjusted, simplified DG-QRAM model: by comparing the resulting FN curve with the risk acceptability criteria according to OMA the need for a detailed analysis is checked (*chapter 4.3, page 39*).

2. Detailed risk analysis for the tunnel applying adjusted, simplified DG-QRAM model: Based on the analysis the need for risk mitigation measures or restrictions for dangerous goods transports can be checked (risk acceptability criteria according to OMA). If a tunnel can not be categorised as an A Tunnel, the risks for alternative transport routes have to be investigated.

As the experience showed, the resulting FN curves of the DG-QRAM model do not fit with the existing risk acceptability criteria according to OMA because the DG-QRAM model focuses mainly on worst-case scenarios. Therefore the following adjustments to the model were implemented for the application in Switzerland:

a. DG Data: adjustment to dangerous goods data and scenario probabilities for Swiss conditions;

b. model parameters: adjustment of accident rates and probabilities for dangerous goods releases for Swiss conditions;
c. extension/adjustments of existing models in DG-QRAM:

- ventilation: additional module for calculation,
- time for detection according to existing technical infrastructure;

d. additional models in DG-QRAM: implementation of a new evacuation model.

2.4. FRANCE

In France, for the purpose of risk evaluation, the following flowchart is considered:

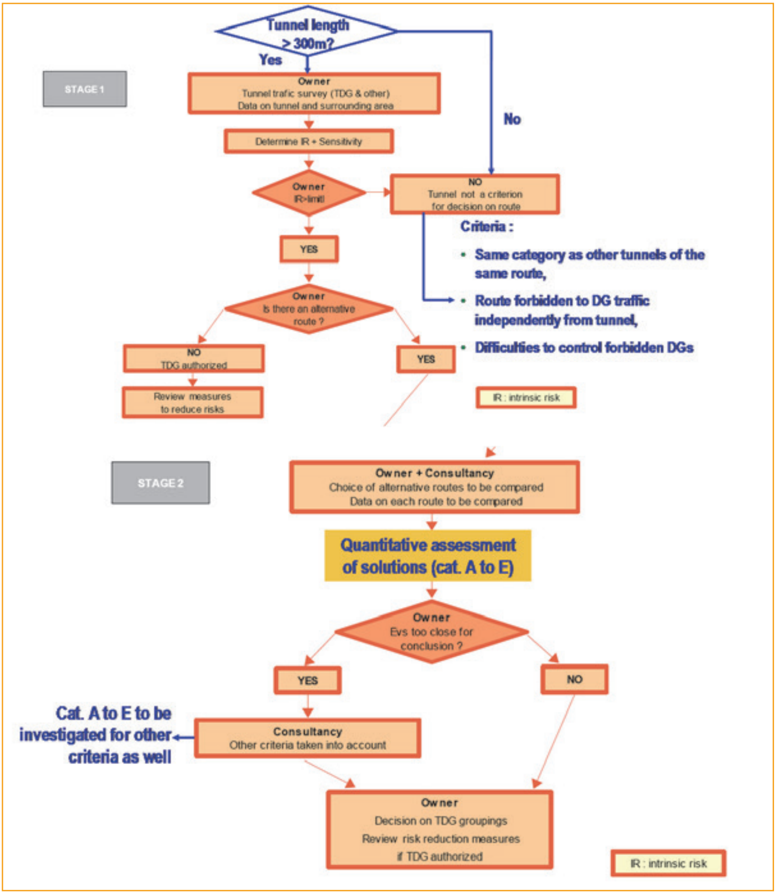

FIGURE 36 – MULTISTAGE PROCESS FOR TUNNEL CLASSIFICATION ACCORDING TO ADR IN FRANCE

On this flowchart, IR is the intrinsic risk value (expected value) for the tunnel. This value is obtained by applying the DG QRA model for the tunnel only, as described above (first step of risk analysis).

Then:

- if IR > 0.001, a QRA study is carried out to compare the tunnel route and possible alternatives, from ADR B category for the considered tunnel to E category, provided that it is possible to find alternative routes where the part of the dangerous goods traffic which is forbidden on the tunnel route can go through;
- if IR < 0.001, risk due to dangerous goods transport is considered as not being an issue, and the decision regarding authorisation or not of dangerous goods transport can be made on the basis of other criteria than those derived from the QRA application.

When a complete QRA study is needed (second step of risk analysis), the OECD/PIARC DG-QRA model is used to compare the risk level due to dangerous goods transported along the tunnel route with other possible solutions where the dangerous goods traffic is totally (category E) or partially (other ADR categories) diverted 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 dangerous goods traffic in the investigated tunnel.