RISK EVALUATION FOR ROAD TUNNELS: CURRENT DEVELOPMENTS

Zulauf Christoph
Ernst Basler + Partner, Zurich/Switzerland

ABSTRACT
Besides the implementation of prescribed safety measures according to guidelines and standards, the application of risk based approaches in the process of tunnel safety management is nowadays an accepted widely used procedure in several countries. Within the risk assessment process, risk evaluation is a very important and sensitive element. 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. Based on the basic principles of risk-based approaches the specific aspects of risk evaluation strategies are discussed.

Keywords: risk assessment, risk analysis, risk evaluation, risk acceptance criteria, safety level, safety targets, expected value, FN diagram, cost-effectiveness

1. INTRODUCTION
Besides the implementation of prescribed safety measures according to guidelines and standards, the application of risk based approaches in the process of tunnel safety management is nowadays an accepted and widely used procedure in several countries.

Risk assessment is a systematic approach to analyse sequences and interrelations in potential incidents or accidents, hereby identifying weak points of the system and recognising possible improvement measures. Three steps characterise the risk assessment process:

- **Risk analysis:** Risk analysis is concerned with the fundamental question: “What might happen and what are the consequences?”. Therefore a set of “typical” scenarios, which can occur in road tunnels, has to be defined and analysed. Risk analysis can be carried out in a qualitative or in a quantitative way or in as a combination of both. For system-based risk assessments quantitative methods are common practice. Thus probabilities of accidents and their consequences for different damage indicators (e.g. in terms of fatalities, injuries, property damage, interruption of services) – considering relevant factors of the system and their interaction – and the resulting risk are assessed.

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

- **Planning of safety measures (Safety management):** If the estimated risk is considered as not acceptable, additional safety measures have to be proposed. Therefore the effectiveness and also cost-effectiveness of different safety measures can be determined by using the initial frequency and consequence analysis of the scenarios which will be positively or negatively affected under the assumption that the investigated safety measure has been implemented. Planning of safety has to answer the question “Which measures are necessary to get a safe (and cost-efficient) system?
The risk assessment process allows a structured, harmonised and transparent assessment of risks for a specific tunnel including the consideration of the relevant influence factors and their interactions. However it should always be kept in mind that every kind of risk analysis – whatever method is used - is a more or less simplified model relying on preconditions and assumptions and is not a copy of reality. Nevertheless assessment models provide a much better understanding of risk-related processes than merely experience-based concepts may ever achieve. Moreover, they allow coming up with the best additional safety measures in terms of risk mitigation and enables a comparison of different alternatives.

2. RISK EVALUATION AS A BASIS FOR DECISION-MAKING

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.

Whereas the first step of the risk assessment process (risk analysis) is a rather scientific process including the assessment frequencies and potential consequences of incidents, risk evaluation goes beyond the domain of technical and engineering experts. The question of risk evaluation concerns decision-makers, responsible authorities, politicians but also laypeople or even society as a whole. Furthermore risk acceptance criteria or acceptable safety levels respectively cannot be defined in an absolute sense. They need to be related to society’s means and ends. Therefore the definition of risk acceptance criteria is a demanding task because it is embedded in a specific legal, social and cultural environment. 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.

3. BACKGROUND TO RISK EVALUATION

3.1. 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. 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:

- **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 (e.g. flying in an aeroplane) than those under personal control (e.g. 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.

3.2. Risk aversion

Regarding the practical application of risk evaluation criteria, one aspect plays an important role, the so 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 risk perception factors mentioned above. 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.

4. PRINCIPLES FOR RISK EVALUATION

4.1. Risk evaluation strategies

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 different aspects of risk perception. Therefore, for the determination of risk evaluation criteria there is no generally applicable "right" or "wrong" safety target. The definition of criteria for risk evaluation takes account of risk perception in various forms, depending on the chosen methodological approach and consequence indicators. 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. In practice, combinations of such strategies are often applied. An illustrating overview of different risk evaluation approaches is given in the following.

4.2. Qualitative risk evaluation strategies

Regarding qualitative risk evaluation there is a wide range of different approaches. The most common approach is the application of prescriptive based criteria such as regulations, standards and guidelines. Other common approaches include:

- Safety audits
- Checklists
- Expert evaluation (e.g. judgement by experts on the basis of scenario analyses)
- Risk matrix / Points schemes

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.

4.3. Quantitative risk evaluation strategies: Societal risk

Societal risk is defined 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 (e.g. operation of a road tunnel). The level and nature of consequences is often measured in terms of loss of life (fatalities). The most common approaches of societal risk evaluation are presented in the following.

4.3.1. Expected value (EV)

A typical 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.

- Application of EV as absolute criteria: The results of a risk analysis - expressed as expected risk value (e.g. (statistically) 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. This approach is easy to apply because it delivers unambiguous results.

- Application of EV as relative criteria: The results of a risk analysis 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 or risk evaluation by means of a “reference tunnel” (e.g. fulfilling all regulative requirements). 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.
4.3.2. FN diagram

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. FN diagrams provide information on the magnitude of consequences in relationship to the (cumulated) frequency of the type of hazard investigated.

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 the following Figure 1. 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.

![FN Diagram with Absolute Risk Acceptance Criteria](image)

**Figure 1:** FN diagram with absolute risk acceptance criteria (fictitious example)

- Application as 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”. 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.

4.3.3. Cost-effectiveness

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.

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. The definition of the risk acceptability criteria is included in the determination of marginal costs. 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 (e.g. a fatality).

4.4. Quantitative risk evaluation strategies: Individual risk

Individual risk is the risk experienced by a single individual (e.g. tunnel user) which is expected to sustain a given level of harm from realisation of specified hazards in a given time period. The number of people exposed to the hazard does not have any impact on the value of the individual risk. As experience shows, 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 road tunnels (e.g. in the Netherlands).

5. PRACTICAL EXAMPLES

5.1. Application of risk evaluation criteria based on expected values (EV)

A typical application of EV as absolute criteria is the evaluation of the risk of transport of dangerous goods (DG) through 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. Such an approach is for example applied in Austria, France, Germany and Greece (strictly linked to the DG-QRAM method):

Table 1: Target values (EV) for transport of DG through tunnels

<table>
<thead>
<tr>
<th>Country</th>
<th>Target value (EV, [fatalities/year])</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria, France, Greece</td>
<td>All scenarios: 1.0 \cdot 10^{-3}</td>
<td>per tunnel</td>
</tr>
<tr>
<td>Germany</td>
<td>Fire: 5.0 \cdot 10^{-3}</td>
<td>per tunnel-km</td>
</tr>
<tr>
<td></td>
<td>Fire and Explosion: 2.2 \cdot 10^{-3}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Explosion: 1.0 \cdot 10^{-6}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Toxic effects: 4.0 \cdot 10^{-4}</td>
<td></td>
</tr>
</tbody>
</table>

This approach is easy to apply because it delivers unambiguous results. However it has to be noted however that risk evaluation based upon an absolute EV 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. fires, explosion 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.
5.2. Application of risk evaluation criteria based on FN diagrams

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. It has to be noted that some of the reference criteria are valid for the risk of the overall traffic whereas some criteria are only valid for the risk of transport of DG through road tunnels. Criteria for transport of DG 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.

One of the practical applications of such criteria can be found in Germany. In the course of the implementation of the ADR tunnel regulation 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 a tunnel will be checked in two steps to determine whether it can allow all DG transports or not. When the DG risks – represented as EV – are evaluated as being too high by means of the simple models of stage 1 (see also chapter 5.1), 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 DG transports. If the risk curve is above the comparative curve, the tunnel will be classified according to requirements, i.e. it will be blocked for DG transport with the appropriate tunnel restriction code and/or constructional, technical or organisational measures will be taken respectively to reduce the risk. The reference criteria for the FN diagram are in Figure 2:

**Figure 2:** German risk criteria for DG Transports through road tunnels

- $F = 0.1 \cdot N^{-2}$ per kilometre per year, for $10 \leq N < 1'000$ fatalities
- $F = 10^{-8}$ per kilometre per year, for $N \geq 1'000$ fatalities

Generally 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 (as for all absolute criteria). 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 not always treated in a consistent way as experience shows.

6. CONCLUSIONS AND RECOMMENDATIONS

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

REFERENCES