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*.

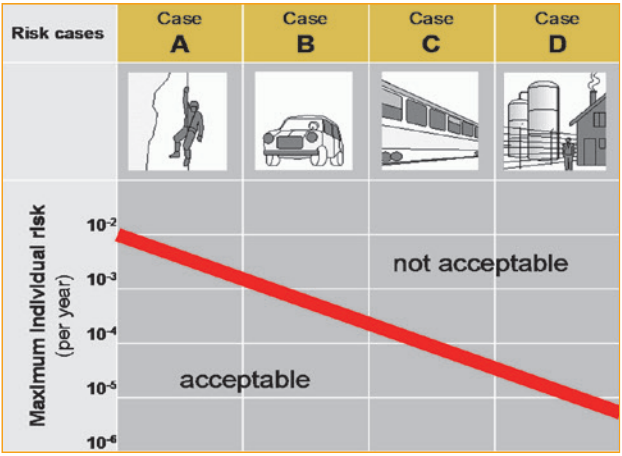

FIGURE 14 – CRITERIA FOR INDIVIDUAL RISK ACCORDING TO BOHNENBLUST AND SLOVIC [16]

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:

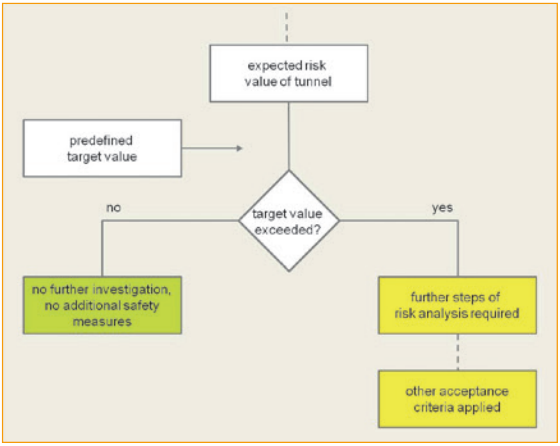

FIGURE 15 – EVALUATION OF DANGEROUS GOODS TRANSPORT RISK FOR TUNNELS

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

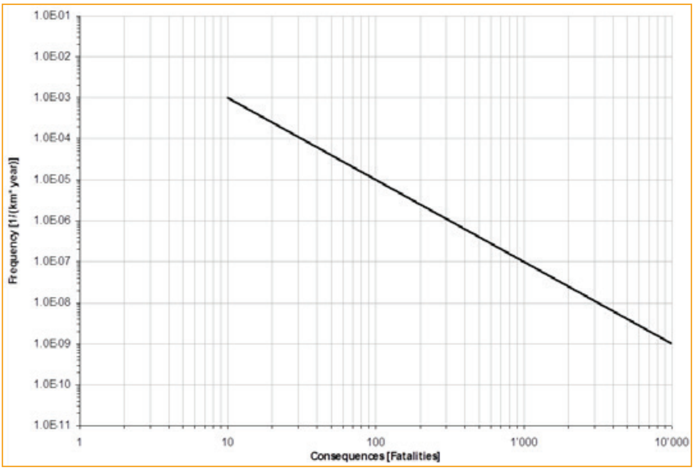

FIGURE 17 – DUTCH RISK CRITERIA FOR ROAD TUNNELS

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

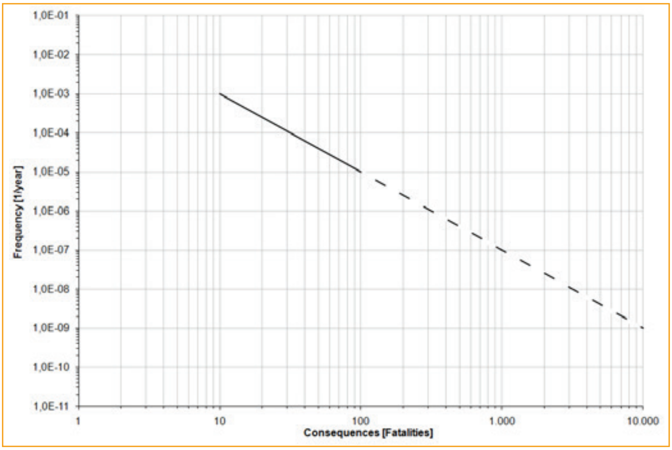

FIGURE 18 – AUSTRIAN RISK CRITERIA FOR DANGEROUS GOODS TRANSPORTS THROUGH ROAD TUNNELS [18]

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

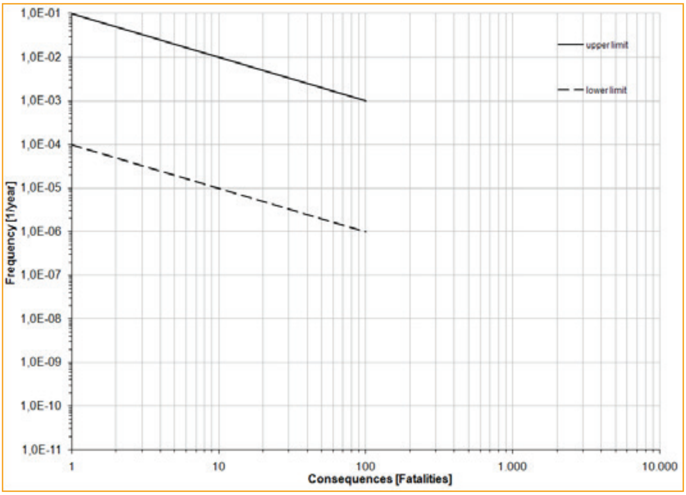

FIGURE 19 – ITALIAN RISK CRITERIA FOR ROAD TUNNELS [20]

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:

$F = 0.1 \cdot N^{-1}$ for $N \geq 1$ 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:

$F = 10^{-3} \cdot N^{-1}$ for $N \geq 1$ 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

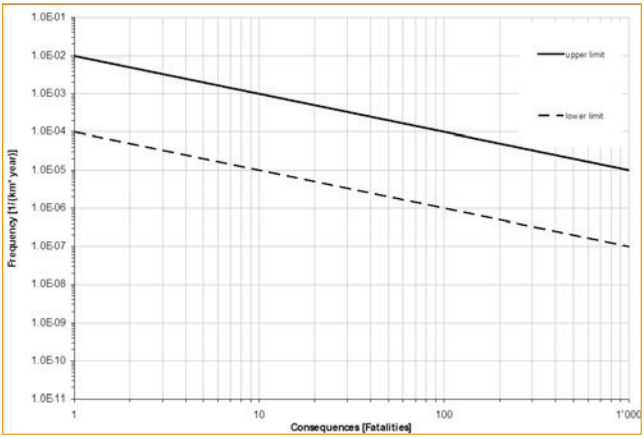

FIGURE 20 – CZECH RISK CRITERIA FOR ROAD TUNNELS

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

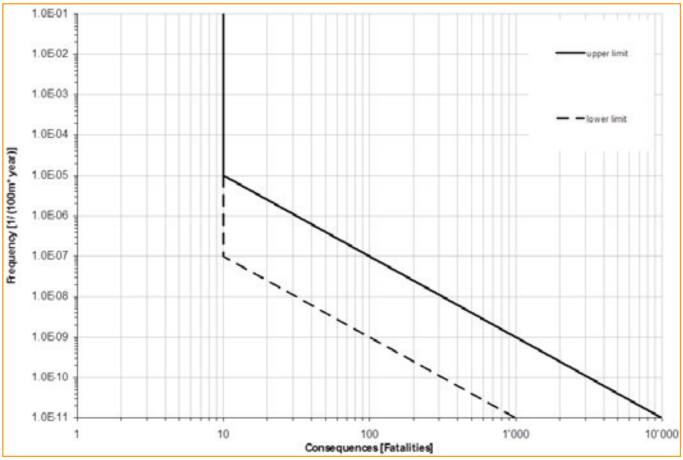

FIGURE 21 – SWISS RISK CRITERIA FOR DANGEROUS GOODS TRANSPORTS (INCLUDING ROAD TUNNELS) [25]

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

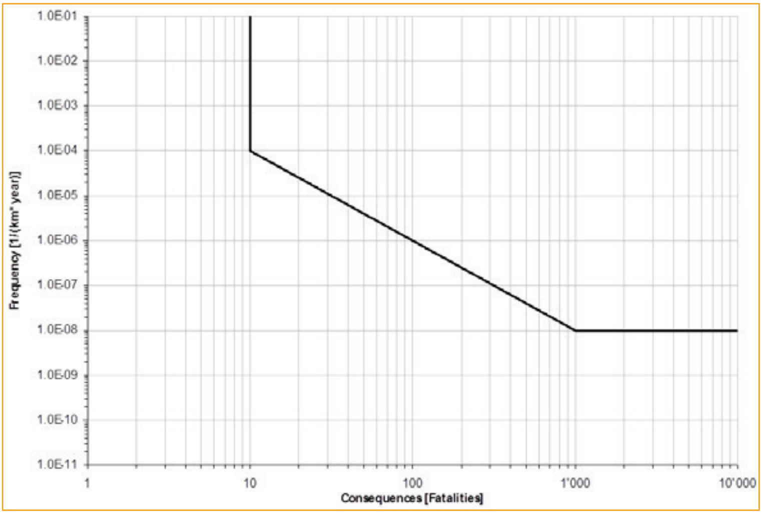

FIGURE 22 – GERMAN RISK CRITERIA FOR DANGEROUS GOODS TRANSPORTS THROUGH ROAD TUNNELS [19]

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.

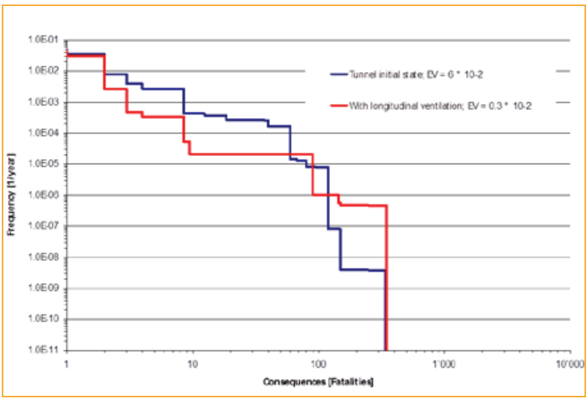

FIGURE 23 – FN CURVES – REPRESENTING THE TUNNEL IN THE STATE AND WITH ADDITIONAL SAFETY MEASURES (EXAMPLE)

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.

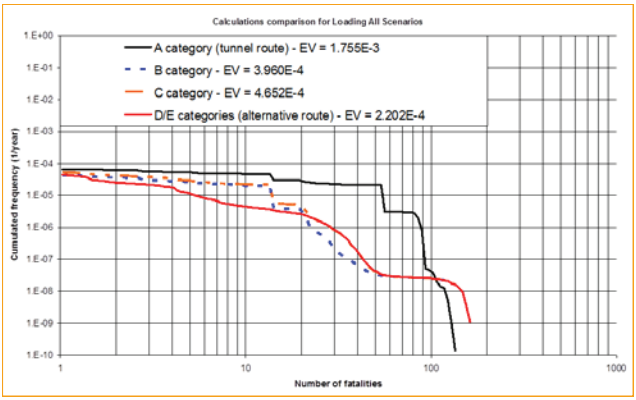

FIGURE 24 – FN CURVES REPRESENTING DIFFERENT OPTIONS REGARDING TUNNEL CATEGORIES FOR DANGEROUS GOODS-TRANSPORT THROUGH TUNNELS (DANGEROUS GOODS TRANSPORT RISKS ONLY)

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
  – $1 \le K/R < 2$: The implementation to be checked by case-on-case study
  – $K/R \ge 2$: 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*.

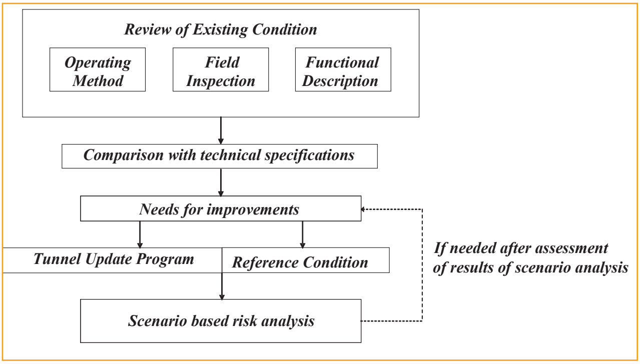

FIGURE 25 – EXAMPLE OF A PROCESS FOR TUNNELS IN OPERATION TO DEFINE AN ACCEPTABLE LEVEL OF SAFETY, APPLYING SCENARIO BASED RISK ANALYSIS

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.

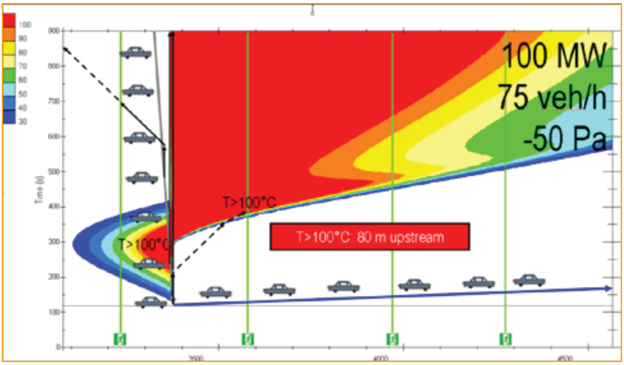

FIGURE 26 – EXAMPLE OF SPACE X TIME GRAPH REPRESENTATIVE OF A HGV FIRE

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.