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# Is International Experience of Risk-Based Decision Making for Road Tunnel Safety Applicable in the Unique US-American Regulatory Environment?

Bernhard Kohl[1], Arnold Dix[2] and Oliver Heger[3]

*1. ILF Group Holding GmbH, Linz, 4020, Austria*

*2. International Tunnelling and Underground Space Association, Monbulk Victoria, 3793, Australia*

*3. ILF Consulting Engineers Austria GmbH, Raaba/Graz, 8074, Austria*

**Abstract:** In the USA, risk-based decision making has not been a common approach to tunnel safety in the past, but this is changing, as concepts such as "equivalency" in the NFPA 502 framework gain acceptance in the USA and elsewhere. In other regions, in particular in Europe, risk assessment techniques have been used for nearly two decades in many jurisdictions as an additional tool to complement the application of prescriptive guidelines and support decisions related to tunnel safety. After some initial difficulties these methods are meanwhile a well-established element of tunnel safety management. There are several tools available which have been practically applied and further developed over years, such as the Austrian tunnel risk model TuRisMo, or the PIARC owned DG-QRAM model. Whereas TuRisMo is a holistic, system-based model, which is best suited to quantify and assess fire risk and associated mitigation measures, DG-QRAM focusses on the risks related to the transport of hazardous materials. Depending on the objectives and the scope of the investigation and the regulatory environment, tunnel risk assessment tools are in use for different purposes, mainly to demonstrate a sufficient level of safety and to decide on and select (additional) risk mitigation measures. The international experience substantiates that the general approach is flexible and that the methods and tools are mature and can be applied for different problems in different environments. First case studies like the risk study on conditions and permissibility of the transport of hazardous materials through the Eisenhower-Johnson-Memorial Tunnel in Colorado demonstrate the applicability of a risk-based concept for decision making in the US-American environment.

**Key words:** Road tunnel safety, quantitative risk assessment, risk-based decision making, tunnel risk model.

## 1. The European Regulatory Environment

Some European countries—namely the Alpine countries, like France, Italy, Switzerland and Austria—have a long tradition in constructing and operating road tunnels. In order to achieve a certain level of standardization these countries began developing design guidelines at national level decades ago. Well-known examples are the Austrian guidelines RVS or the German RABT (now called EABT-80/100). These guidelines implicitly also addressed safety aspects. A tunnel was regarded as sufficiently safe if its design/current status was in line with prescriptive guidelines. Residual risks were neither addressed nor evaluated. As a consequence of the major tunnel fires in 1999-2001, the EC-Directive (54/2004/54/EC) on minimum safety requirements for tunnels in the Trans-European Road Network Directive 2004/54/EC [1] was issued. It defines unified minimum safety requirements for tunnels on the Trans-European Road Network and at the same time established risk assessment as an obligatory new tool for tunnel safety management. Article 13 of this Directive governs the use of risk assessment in the context of road tunnel safety, stipulating that "Member States shall ensure that, at national level, a detailed and well-defined methodology,

**Corresponding author:** Bernhard Kohl, Dipl. Ing. in civil engineering, research fields: tunnel safety, quantitative risk assessment.

corresponding to the best available practices, is used...”

The European Directive had to be implemented in the national legislations of the EU Member States, thus setting the frame for a subsequent adaptation of the national tunnel design guidelines in those countries who had already tunnelling guidelines before. Typically these national guidelines are more strict and more specific than the EC-Directive. The EC-Directive is formally in force for tunnels on the Trans-European Road Network only. Tunnels on this network, which were not compliant with the requirements of the EC-Directive, had to be upgraded until a certain date (different for different Member States—depending on the number of tunnels, they had to deal with). This led to a harmonization of the safety standard on the Trans-European road network and also beyond, as many countries expanded the area of validity of these new regulations to other parts of their national road network as well.

During this intense upgrading process risk assessment played an important role as the EC-Directive also introduces the principle of compensation. This principle defines that alternative risk reduction measures can be used if at least an equivalent level of safety can be achieved, and this can be proven by risk assessment. Whereas the EC-Directive is very strict with respect to such derogations from the minimum safety requirements—only limited derogations caused by imperative reasons or in case of the use of innovative safety equipment are allowed—this becomes much more flexible with respect to derogations from the regulations of the national guidelines (as long as the minimum safety level can be fulfilled) as well as for tunnels outside the Trans- European Road Network, the area of formal validity of the EC-Directive. Due to the big investments needed to implement these ambitious tunnel renovation programs, the operators became familiar with these new tools and learned to use it for decision making in order to optimize the measures needed to improve tunnel safety from a cost-benefit perspective. The growing experience and practice in tunnel risk assessment in Europe also informed tunnel projects in other countries around the world, thus establishing risk assessment as reliable decision support tool in the context of tunnel safety. At the same time, the World Road Association PIARC reflected the application of risk assessment in road tunnels in several reports, addressing methods [2], approaches for risk evaluation [3], and feedback from experience [4].

## 2. Practical Approaches

### *2.1 Methods and Tools*

Following the major risk-based decision making reforms in the EU at the turn of the century several different risk assessment methodologies have been developed, adopted, and successfully used in different national regulatory environments. Based on practical experience and needs, some of these methods meanwhile were developed further, by optimizing approaches, further improving the quality and quantity of input data, and adapting application rules, including strategies for risk evaluation, thus expanding their range of applicability and the reliability of their use. In parallel a lot of data were collected which then were used to inform the methods themselves as well as the assessment of all kinds of safety measures.

These methods analyze the societal risk of tunnel users; they are either system-based (i.e., they address the overall risk of a tunnel in a holistic manner) or scenario-based (i.e., they investigate a few preselected and predefined scenarios). Typical risk parameters are either the EV (expected risk value) or an F/N curve (frequency/consequence curve) or both [3].

Some of these methods are also applied at international level, two of them are explained a bit more in detail, to show how they are working: The Austrian Tunnel Risk Model TuRisMo [5-7] and the recently upgraded PIARC-owned model for the assessment of the transport of hazardous materials through road tunnels, DG-QRAM [8].

The Austrian methodology as defined in the national guideline [5] uses a fully integrated approach that allows for the detailed analysis of many kinds of safety measures and for interactions between different safety measures. Factors such as the installed equipment and boundary conditions such as traffic conditions are taken into account rigorously. The method combines a quantitative frequency analysis (event-tree approach) based on statistical evaluations and a quantitative consequence analysis that includes (i) a (mechanical) collision-only part and (ii) a distinct fire consequence model. Fig. 1 shows a schematic representation of the overall structure of the method.

The Austrian Tunnel Risk Model has a modular structure, which makes it very flexible and thus adaptable to different types of tunnels as well as scopes. It is also possible to use one of the modules in very specific applications—as for instance described in the US case study at the end of the paper.

To give an impression of the capabilities of this model with respect to fire risk assessment the fire consequence model of TuRisMo is explained in more detail:

- In a standardized event tree, a representative set of scenarios—for collisions as well as for fires—is developed and the respective probabilities are calculated.
- For each distinct fire scenario explicitly considered in the event tree, a set of detailed scenarios with varying local parameters are generated based on the probability distribution of the influencing parameters;
- For each of these detailed fire scenarios, a transient one-dimensional airflow simulation is performed, taking into account all important influencing factors such as traffic volume, fire location, ventilation design and meteorological boundary conditions;
- The predicted development of the longitudinal airflow velocities is then used as boundary condition in a three-dimensional Computational Fluid Dynamic (CFD) simulation (applying FDS - Fire Dynamic Simulator) in which local effects such as back-layering and smoke stratification are examined;
- Visibility-, heat- and toxic-gas concentrations generated in the three-dimensional CFD simulation are then combined with person-exposure distributions dependent upon the traffic configuration after the incident;

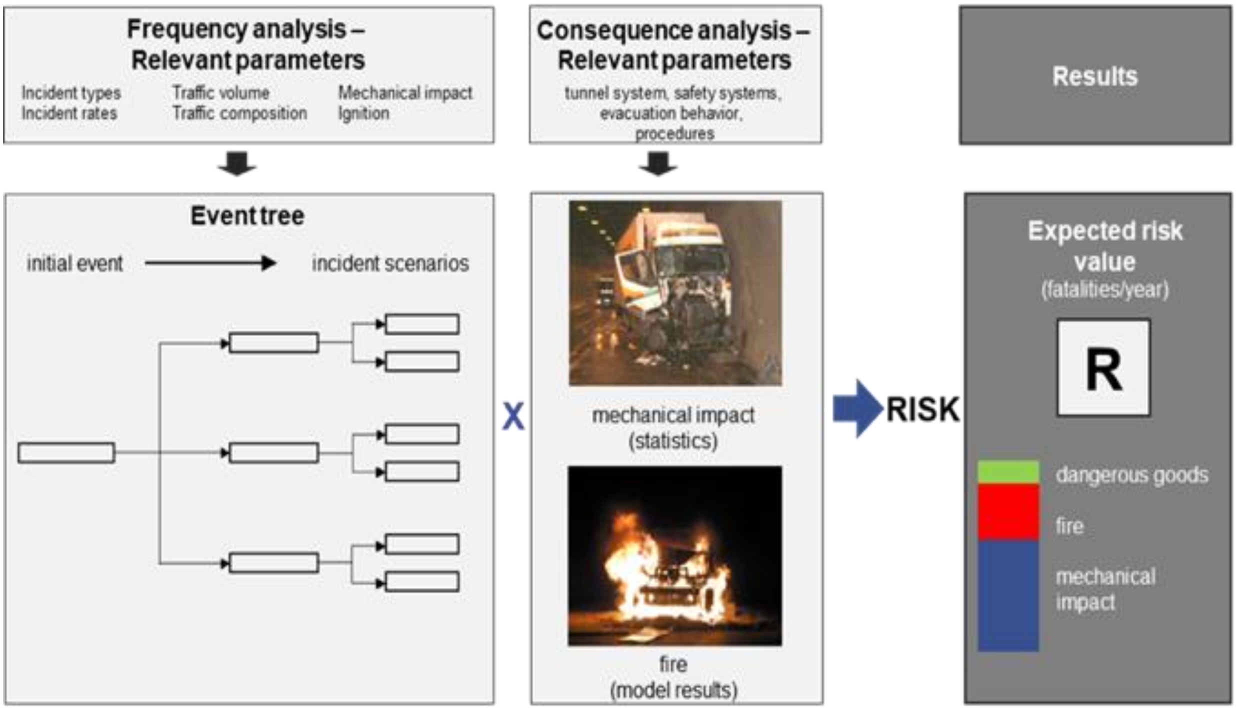


**Fig. 1 Scheme of an event-tree-based road tunnel risk model.**

- Based on this superposition and using an accumulation and intoxication model describing the effects of fire hazards on evacuation speed and survivability of persons [4], the expected total number of fatalities is computed. The whole process is then repeated for the next detailed scenario.
- By means of statistical superposition of the distinct scenarios, combined damage-extent values are generated for each global scenario in the event tree. This enables the evaluation of an overall risk-expectation value for the tunnel based on the statistically expected number of fatalities per year.

Details of the various other sub-models of the overall method have been given elsewhere [5, 7, 9] and are not reproduced herein.

Whereas risk models like TuRisMo have a broad range of application and are typically applied to decide on (additional) safety measures for a tunnel, the Dangerous Goods Quantitative Risk Assessment Model DG-QRAM [8] is focusing on the risk of dangerous goods transports and can be used for the assessment of the DG-risk of a tunnel as well as for the comparison of 2 (or more) transport routes, including tunnels as well as open road sections.

In a nutshell, DG-QRAM is based on 13 scenarios describing different hazards of a release of hazardous material inside or outside a tunnel [8]. The societal risk of each scenario can be evaluated for different routes. The calculation takes into account accident frequencies (derived from historical data), physical consequences of incidents within tunnel and along open routes based on relatively simple physical consequence models, taking into account effects of hazards (such as explosions, exposure to toxic substances, heat or smoke) on people as well as escape and sheltering effects. The societal risk calculated reflects the range of possible outcomes of a HAZMAT incident, each with different probabilities.

Incidents involving dangerous goods may have a very low probability but at the same time the potential of seriously affecting a high number of people. This relationship is illustrated by depicting the risk in an F/N curve (Fig. 2) where F is the frequency of N or more fatalities (and/or injuries). Each curve can also be evaluated in terms of a single value representing the average number of fatalities per year (the Expected Risk Value). The F-N curves can be produced for fatalities and/or injuries, and for road users and/or the local population. Then the scenario results can be aggregated as needed.

These two risk analysis methods described above are two typical examples, but there are several others, some of them similar, others quite different. The cause for this diversity can be explained by the significant difference in the tunnel portfolio of different countries: whereas for instance the Netherlands have a limited number of tunnels (mostly immersed tunnels), all of them unidirectional with 2 tubes and longitudinal ventilation, relatively short but with a very high traffic load (and hence the Dutch method can only handle this type of tunnels), Norway on the other hand has a high number of long bidirectional tunnels with steep gradients and low traffic, which requires other specifications for an appropriate risk assessment tool.

### *2.2 Risk Evaluation Concepts*

The complexity of risk assessment methodologies and the many different ways of applying them in practice involves that there are no unified risk acceptance criteria for road tunnels, they in fact depend on the method, the use case and the regulatory environment. In practice in the majority of cases relative risk evaluation approaches rather than absolute risk acceptance criteria are used. In case of risk evaluation by relative comparison the risk profile of the existing state of a tunnel is compared to a reference state, which is representing a sufficient level of safety. Typically, this “Reference Tunnel” is a similar tunnel which fully complies with the regulatory requirements, which per definition is regarded as sufficiently safe. Fig. 3 shows the results of an investigation of several measures reducing fire risk in a tunnel exceeding the reference risk value.

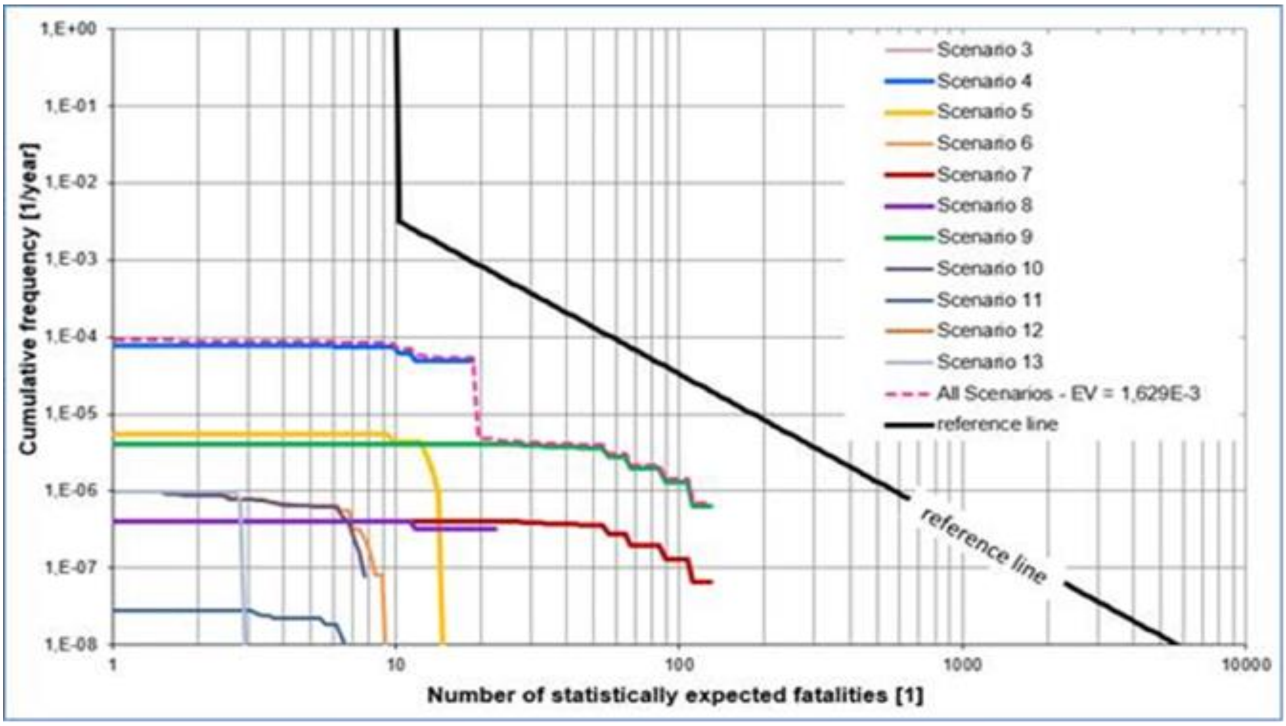


**Fig. 2** F/N diagram, depicting the results of a HAZMAT risk assessment of a tunnel, applying DG-QRAM; the figure also includes a risk reference line as absolute risk acceptance criteria.

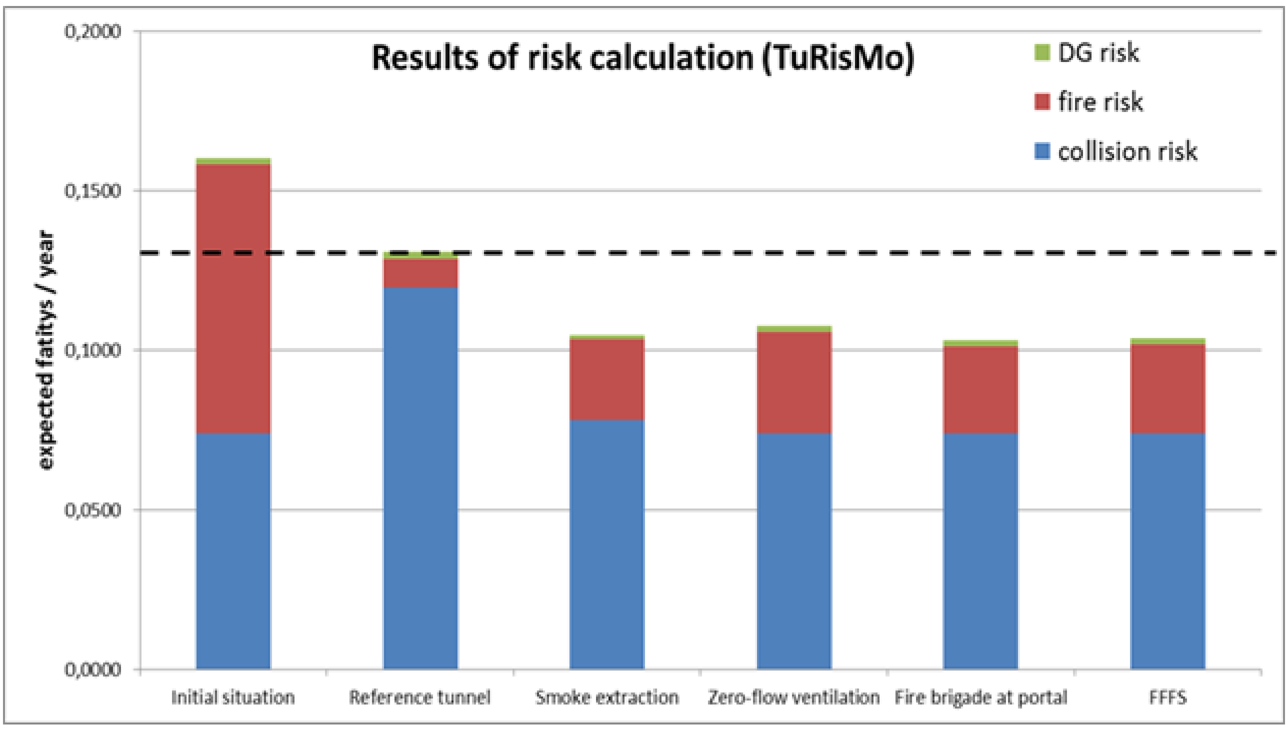


**Fig. 3** Reference tunnel approach: the risk of the reference tunnel defines the maximum admissible risk level.

This comparative method is independent from absolute acceptability criteria (which in many countries do not exist) and is compatible with the "Globally At Least Equivalent" principle of risk acceptability [3]. This approach has several advantages:

- It establishes a link between the prescriptive and the risk-based approach to tunnel safety, by "translating" regulatory requirements into a quantitative risk profile; hence it is consistent with many regulations like for instance the EC-Directive;
- It is flexible and can even be applied in countries which do not have their own tunnel regulations, because for almost all use cases a plausible reference case can be defined; a real case is the Waterview Tunnel in Auckland, New Zealand [10]: for this tunnel in the permission the number of hours with congested traffic per year was strictly limited; in the commissioning phase the tunnel operator became afraid that this requirement maybe could not be met; in a risk study it could then be demonstrated, that also in this case the risk level implicitly defined in the permission would not be exceeded;
- It is less sensitive to the fuzziness which is inherent in all risk assessment methodologies, because the same method and the same input parameters are used for both steps of the analysis—the reference tunnel and the real tunnel—except those, which are describing the differences;
- However, the definition of the reference tunnel is not always straight forward and therefore some guidance is given in national regulations.

However, there are some use cases, for which—at least in some stages of the evaluation process—absolute risk evaluation criteria are applied as well. A typical example is the transport of dangerous goods through road tunnels: in some national regulations absolute risk acceptance curves have been defined which are used to decide on transport limitations for a specific tunnel (Fig. 2). Typically, this is only one specific step which is embedded into a broader decision making procedure. It is important to mention that the use of absolute acceptance criteria involves several problematic aspects and is only applicable if it is linked to a precisely defined method (in this case the DG-QRAM model, which is a software tool).

Another principle which can be applied for decision making, is the "Marginal Cost Principle". This approach is focusing on the economic point of view, by defining a maximum amount of money to be spent for a saved life (the marginal cost); in practice this means, that only those safety measures have to be implemented which show a cost/benefit ratio below the defined benchmark. Such an approach is for instance applied in Switzerland.

In whatever manner the results of a risk assessment study are evaluated, it must be pointed out that, this is only one aspect and for the final decision the results need to be embedded and discussed in a broader context. Typical other aspects to be considered are for instance operational implications, potential secondary effects e.g. on the environment or on traffic safety in other sections of the road network, and of course on cost.

## 3. Typical Applications of Road Tunnel Risk Assessment

Depending on the objectives and the scope of the investigation and the regulatory environment tunnel risk assessment tools are in use for mainly two different purposes:

- to demonstrate a sufficient safety level;
- to decide on and select (additional) risk mitigation measures.

Typical use cases for risk-based decision making are:

- Tunnels with deviations from prescriptive requirements

Risk assessment can be used to prove that with alternative measures, an equivalent safety level can be achieved; the detailed conditions for such an application depend on the regulatory environment of a country; for instance—as explained above—the minimum safety requirements of EC Directive 2004/54/EC [1] provide such a frame with respect to derogations from national guidelines.

- Tunnels with "Special Characteristics"

The term "special characteristics", as defined in the EC-Directive, addresses specific circumstances or conditions with respect to parameters of tunnel infrastructure, traffic or operation, which may have a significant influence on risk. Examples for such a special characteristic are a high gradient (exceeding 3%) or a high number of heavy goods vehicles (exceeding 15%); in such cases the EC-Directive requires a risk assessment and compensation measures to ensure an acceptable level of safety.

- Upgrading of Existing Tunnels (Ventilation System & Emergency Exits)

For the rehabilitation of existing tunnels often more restrictions apply than for new tunnels, in particular if changes of the ventilation system or of the egress conditions would be required. Hence, upgrading them to updated prescriptive requirements may lead to disproportionate cost or may even be impossible. Risk assessment can be applied to select the best suitable combination of measures to compensate the shortcomings.

- Optimization of Safety Planning from a Cost-Benefit Perspective

Quantitative risk assessment delivers accurate, quantitative information about the efficiency of individual safety measures with respect to their risk reduction potential. In combination with the cost of these measures a cost/benefit ratio can be calculated, which supports an efficient use of the (always limited) financial resources available for the improvement of tunnel safety.

- Decisions on Operational Strategies for Emergencies

The presence of safety systems like traffic management systems or tunnel ventilation is a prerequisite for a successful emergency response, of course, but in reality, tunnel safety is very much influenced by the way, how these systems are operated in an emergency. The influence of operational strategies in emergency response is often underestimated and opens up room for improvement. A thorough risk assessment may trigger ideas for improvement and provide the basis for a reliable assessment of their efficiency. Operational measures often are cheap, efficient, and easy to implement.

- Specific operational conditions with reduced safety level (e.g. in construction phases)

Risk assessment can be used to quantify this influence and to investigate potential compensation measures. However, the decision about acceptability of an increased risk for a limited time needs to be taken in a broader context.

- Commissioning of new tunnels in case of deviations from conditions defined in the permission

It may happen that restrictions during construction of a new tunnel require some changes of the design or changing boundary conditions may cause unforeseen special characteristics. In such a case risk assessment can be used to demonstrate that the tunnel is still compliant with the status of the permission, possibly with additional measures.

- Decisions on admissibility of DG-Transport

For decisions on transport limitations for HAZMAT on tunnel routes specific risk models are required. The most commonly used risk model in this context is DG-QRAM.

In many countries the basis for the DG-studies is the ADR tunnel regulations (ADR—agreement concerning the international carriage of dangerous goods by road). Within ADR tunnels are assigned a category from A to E to control the transport of dangerous goods through them. Tunnels marked as Category A are considered to be low risk, which means there are no restrictions when transporting dangerous goods through them. Category E marked tunnels are considered to be high risk, which means very few dangerous goods are allowed to be transported through them. Except for category A, all other categories are provoking transport restrictions for a specific tunnel (increasing, from B to E).

In this context, DG-QRAM may be used in the following manner [8]:

- Assess the societal risks due to dangerous goods transport for different transport routes, with and without tunnels, and compare the results to each other;
- Compare the societal risk of a tunnel or along a route with some absolute reference criteria. This includes all sorts of criteria, such as reference criteria for the expected risk value as well as one or more threshold F-N curves (e.g., see Fig. 2).
- Assess the societal risks for each ADR category (A to E) of a given tunnel in order to decide on the categorization and the related transport limitations.

In some countries inside and outside Europe (as—just recently—in Australia) various methodical frameworks were developed to guide the decision making process at national level in accordance with the national legal and regulatory environment.

## 4. The US-American Regulatory Environment

The United States, European Union and Australia share important similarities in terms of the administration of tunnel road safety and the law. In each regulatory framework the "member states" are responsible for setting and enforcing local laws and professional standards. It is acknowledged (of course) that the central government (such as administered from Brussels, Washington and Canberra respectively) has the overarching power to regulate defined matters (such as the trans-European road network, the Interstate and the National network respectively) and to influence state decisions via funding incentives—the States uniquely control the professional standards expected of their licenced engineers making safety critical decisions.

This means that an engineer performing a risk based decision making exercise must be mindful of how the state courts will judge their risk based decision making in the event of loss, injury or death arising in a tunnel they have actively been managing.

This is important because following prescriptive requirements in a code or standard is often perceived as a simple way of demonstrating that a decision made was appropriate. However, this simplistic approach can put an engineer at risk if the code itself can be demonstrated to be deficient and outdated. For example safety in a dangerous goods tunnel might well benefit from rapid implementation of tunnel closures using augmented digital image analysis—albeit that such technologies are not in the current standards. In the authors' experience "standards" are typically in the order of at least a decade behind the latest innovations in tunnel safety—and therein lies the challenge for practitioners' making informed decisions.

## 5. Application of Road Tunnel Risk Assessment in the US-American Environment

Undertaking a risk based analysis as part of the decision making process in the United States demands special attention to several United States specific issues.

- Firstly and most importantly, the United States has a long history of developing prescriptive standards that prescribe exactly what measures are required to operate a safe tunnel. This approach has created a culture of compliance with predetermined sets of prescriptive requirements defining exactly what is safe. It is the only country known to the authors in which "code engineers" are recognized as a legitimate class of engineers—evidencing the elevation of administrative functions to the level of engineering. This means that risk based decision making is contrary to longstanding engineering practices and is therefore the subject of suspicion within an engineering culture of simplistic regulatory compliance.
- Secondly, each state has its own unique legal framework within which road authorities and other agencies must discharge their statutory and common law duties. Each state's legal framework must be understood in order to ensure the authorities have discharged their duties.
- Thirdly, it is related to the second point above—the legal responsibilities of individual engineers and organizations must be understood within the state legal context and any peculiar contractual requirements of a project.

Interestingly, this prescriptive landscape has been changing with the introduction of the concept of "equivalency" into standards such as NFPA 502 and NFPA 130. The concept of "equivalency" uses the prescriptive requirements of the standard as the definition of safe enough—and empowers "equivalent to or superior" alternative solutions. By this important mechanism comparative risk assessment tools now assume a role in demonstrating the safety performance of non-prescribed alternative "equivalent" solutions.

In combination these unique State factors must be integrated within the decision-making process of delivering tunnel safety using risk based tunnel safety tools.

## 6. US Case Study: The Eisenhower-Johnson-Memorial Tunnel

As a reaction to SB (Senate Bill) 19-032, CDOT (Colorado Department of Transportation) together with the Stantec Consulting Services Inc. risk assessment team initialized a quantitative investigation to study whether and under what circumstances hazardous material transports should be allowed in the EJMTs (Eisenhower/Johnson Memorial Tunnels) [11]. The EJMTs are located approximately 60 miles west of Denver, Colorado, on Interstate 70 at an elevation of 11,000 feet. Each tunnel consists of two 8,900-foot long lanes that carry one-way traffic. In current practice, hazardous materials trucks, such as gasoline tankers, are generally not allowed to pass through EJMT and are routed over Loveland Pass via US Highway 6 (US 6). Loveland Pass is a difficult route, with tight switchbacks and steep grades; it is a route that often must be closed due to snow, which creates even more hazardous driving conditions and avalanche danger. In the scope of this project, CDOT and the Stantec risk assessment team sought to estimate the risk associated with the transport of hazardous materials on the US 6 route including Loveland Pass and compare this risk estimate to the risk for the Interstate 70 route including the EJMT in a quantitative manner.

One of the major issues CDOT is facing with respect to the transport of hazardous materials, either over Loveland Pass or through EJMT, is to balance the low probabilities but potentially large consequences of events involving hazardous materials with the daily need for the safe transport of people, energy, and chemicals that facilitate Colorado's economy. As the risk for residents and road users is one of CDOTs major concerns, the methodology selected for the quantitative comparison had to be capable of assessing personal risk in open road as well as tunnel sections. This made DG-QRAM a natural choice. While comparing the general risk of open road sections and sections including tunnels is one of the core features of DG-QRAM, it often falls short on the detailed assessment of specific tunnel characteristics like complex tunnel ventilation systems or fixed fire suppression systems. Therefore, TuRisMo was selected to complement the DG-QRAM assessment and both tools were combined in a novel homogenized approach. DG-QRAM was used to estimate the general risk for both routes. TuRisMo was applied for the tunnel section to calculate risk reduction factors representing the effect of specific mitigation measures which cannot be accounted for by DG-QRAM directly. This combination allowed for the quantitative comparison of both routes also taking the characteristic safety design of EJMT into account.

The assessment is still ongoing, but the results obtained in the first phase suggest that overall risk can indeed be reduced and risk reduction measures, promising for their risk reduction capabilities and their estimated cost-effectiveness, were selected for further analysis.

## 7. Conclusions

The United States is currently renewing much of its aging critical tunnel transportation infrastructure and building other new sections. Systematic risk assessment techniques and experiences from Europe provide a useful intellectual framework and history of application of new tunnel risk management tools such as DG-QRAM and TuRisMo that can be critically considered for application in the unique United States infrastructure renewal context.

The long and proud traditions of prescriptive tunnel safety in the United States is well placed to embrace modern concepts and techniques of systematic risk assessment from other advanced and risk sensitive jurisdictions such as the European Union and Australia.

Embracing systematic tunnel risk assessment methodologies in the United States demands translation of the techniques into the United States and unique American State regulatory and customary practices.

The use of DG-QRAM and TuRisMo as part of the systematic and considered upgrade of the EJMT provides a useful case study of how international techniques can be adapted to the unique circumstances of a refurbishment project in Colorado, an example State of the United States.

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