RISK ANALYSIS AS DECISIONMAKING TOOL FOR TUNNEL DESIGN AND OPERATION

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ABSTRACT

The EC-Directive 2004/54/EC established risk analysis as performance based approach for the assessment of road tunnel safety. The paper presents a survey of typical applications for risk analysis, focussing on its application as decision making tool. 3 case studies provide insight in typical problems addressed by risk analysis: For the existing Učka Tunnel in Croatia, the decision on the ventilation system of the planed second tube was taken on the basis of a risk analysis, for the Markovec tunnel in Slovenia, the influence of specific wind conditions on tunnel risk and its consequences on the layout of the ventilation were studied with a scenario-based method and for the Heidkopf tunnel in Germany the decision on the acceptability of the transport of dangerous goods was taken on the basis of a risk-based approach.

Furthermore the case studies demonstrate that different risk analysis methods and risk evaluation strategies are required to be able to specifically address different kinds of problems.

Keywords: Risk analysis, risk based decision making, system-based risk analysis, scenario-based risk analysis

1. WHY APPLYING RISK ANALYSIS

Since the EC-Directive 2004/54/EC [1] introduced risk analysis as a performance based approach for the assessment of safety standards, it has been established as complementary element to the traditional prescriptive based approach to tunnel safety. The application of this tool has become more and more common for various purposes [2]:

- To check the general consistency of safety planning
- To choose between alternatives – in design as well as in operation
- To evaluate (additional) risk mitigation measures
- To optimize safety planning in terms of cost effectiveness
- To demonstrate safety in case of deviations from prescriptions

In the past few years a dynamic development took place in terms of evolution of quanitative risk models, which enable the user to draw conclusions on the basis of quantitative results reflecting the influence on safety of specific features of tunnel design or operation. The improvement of risk models – more and more based on simulations – made the evaluation of even complex situations possible, thus providing a better basis for an informed decision for the people responsible for tunnel safety - including aspects of financial implications of their decision.

5 typical fields of application can be defined for the use of risk analysis as a support tool for decisions in tunnel design and tunnel operation:

- Upgrading of existing tunnels: older tunnels often do not fulfil modern tunnel safety standards. In an upgrading process the safety standard has to be improved. In existing tunnels however – other than in new ones - often severe technical, operational and financial restraints have to be taken into account, so that it may not be possible (or not adequate) to just adopt it to new standards. In such situations, typically different design solutions are developed which have to be evaluated in terms of their consequences on safety, operation and cost – a typical application of risk analysis as evaluation tool for tunnel safety. In this context, reference is made to the new PIARC report "Assessing and Improving Safety of Existing Road Tunnels" which defines a clear procedure for the implementation of safety in the upgrading process. This report was presented at the World Road Congress in Mexico City in November 2011 and will be published in near future in the PIARC virtual library.
- Safety relevant design decisions for new tunnels: also for new tunnels, sometimes different options are available to fulfil a given safety standard or additional safety measures are required to compensate a special characteristic; in both cases risk analysis may contribute to decision making, by providing information on the effects on safety of the different design options, which can be used as input data for a cost-effectiveness assessment. The most common application in practice are decisions on the design of the ventilation system.
- Safety relevant design decisions for tunnel operation: operational regulations influencing safety are an option for additional safety measures for existing as well as for new tunnels. For the transport of dangerous goods this type of measure has been established on a regulative basis: every tunnel has to be allocated to one of five ADR tunnel categories (category A: all dangerous goods allowed – category E: all dangerous goods forbidden). The decision, which classes of dangerous products are allowed to be transported along the tunnel route or are to be diverted on alternative routes is typically taken on the basis of the results of a risk analysis
- Investigation of specific non standard situations, with lack of information or unclear situations in tunnel regulations; risk based studies on such topics may provide results and conclusions of general interest, giving input to tunnel design for comparable situations.
- Giving input to modifications of tunnel design guidelines: regulations on tunnel design were developed based on experience and expert judgement; the experience of the increasing application of quantitative risk analysis models indicate, that specific definitions may require modifications if seen from a mere safety point of view. Research activities on such topics are under way aiming to provide a proper basis for the discussion of such adaptions – for instance the project "Procedure for the definition of the ventilation system of road tunnels" for the German Federal Highway Research Institute or the research activities of the upgrading of the Austrian Tunnel Risk Model TuRisMo

This paper is focussing on three case studies presenting three different practical situations which require the application of a risk-based approach as a basis for decision making.

2. REGULATIVE BACKGROUND FOR DECISION MAKING ON THE BASIS OF A RISK ANALYSIS

Although the EC Directive 200/54/EC defines "minimum safety requirements" (limited) derogations of the requirements in Annex I are allowed under specific conditions. The basic principle for the acceptability of such exceptions is always the compensation by alternative safety measures, resulting in an equivalent or higher safety level, which has to be demonstrated by a risk analysis. This principle is addressed in several chapters in the Directive, e.g. in article 3 (for existing tunnels) or in chapter 1.2.1 of Annex I, and it is always linked to specific conditions like missing feasibility or disproportionate cost.

National tunnel safety regulations also refer to risk analysis as a basis for decision making. The Austrian Tunnel Safety Law [3], for instance, implements the minimum safety requirements defined in the EC Directive as minimum standard for all tunnels of the Austrian highway network; at the same time it establishes the principle for limited derogations defined above as general principle for exceptions for all prescriptive requirements layed down in Annex I (however, for tunnels on the transeuropean road network the specific definitions of the Directive are applied). In the German tunnel guideline RABT [4] risk based decision making is established as well: for instance, for tunnels with bidirectional or congested traffic with a length between 600m and 1.200m the decision on the ventilation system has to be taken on the basis of a risk analysis [5].

3. CASE STUDIES

3.1. Učka Tunnel (Croatia)

The problem

The Učka Tunnel is a 5,062 km long tunnel in Istria with one tube and bidirectional traffic, built in 1981. In the next years, a second tube will be built. The risk assessment study covers the new tunnel configuration. The focus of the study is on the decision on the ventilation system of the future tunnel configuration; furthermore it is intended to define safety requirements for the tunnel design.

Usually, the selection of the ventilation system is based on definitions in regulations. In Croatia, at the time being there are no specific national tunnel regulations; in practice the Austrian regulations RVS are applied. In RVS 09.02.31 [5] a limit of 3 km for the tunnel length is defined for the application of longitudinal ventilation systems. For tunnels longer than 3 km a transversal ventilation system is required. In practice, there are several examples for unidirectional tunnels longer than 3km equipped with a longitudinal ventilation system, for example, the 5,8 km long Strenger tunnel located in Austria at the S16.

The existing Učka Tunnel is equipped with a longitudinal ventilation system. The implementation of a transversal ventilation system in the existing tunnel tube would cause big technical problems (the tunnel cross section would have to be enlarged) and major costs; for the new tunnel tube a transversal ventilation system would be a major cost parameter as well.

From the safety point of view, a ventilation system with smoke extraction in principle shows advantages (because in fire scenarios, smoke can be sucked off), however in tunnels with two tubes and unidirectional traffic and low probability of congested traffic, the benefit is only minor and highly disproportionate to the resulting costs. Furthermore, the Učka Tunnel is a tunnel with very specific conditions and a series of non-standard safety measures already installed.

The approach

As the Austrian tunnel design guidelines RVS are applied in Croatia, as method for the risk assessment study the Austrian tunnel risk model TuRisMo (defined in RVS 09.03.11) was chosen. TuRisMo is a system-based risk model, expressing tunnel risk as expected risk value, distinguishing between risk due to mechanical accidents, fire risk and risk involving effects of dangerous goods. However, for this specific application an extended version of the model was applied: additionally to the 5MW and 30MW fire scenarios a 100MW fire scenario was implemented in the event tree and the consequences of tunnel fires where specifically calculated for the Učka tunnel, thus replacing the standardized RVS damage values, which were nor applicable for this specific situation. For the simulation of smoke propagation in Učka tunel a 3D CFD model (FDS Fire Dynamic Simulator [6]) was applied and the results were transferred into an evacuation simulation model (bulidingExodus [7]) to calculate the consequences on people in the tunnel

For the evaluation of the results of the risk analysis, a relative approach is applied: the risk of the real future tunnel is compared to the risk of reference tunnels, representing the admissible safety level. In this specific case, several comparisons to different reference tunnels are made:

- Comparison **Učka tunnel - Reference tunnel EC-Directive**
  to demonstrate an adequate safety level or highlight requirements for additional safety measures with respect to minimum safety requirements according to EC-Directive
- Comparison **Učka tunnel – Reference Tunnel RVS (transversal ventilation)**
  to demonstrate, that the benefit of transversal ventilation can be compensated by existing safety measures or to highlight requirements for further compensation, in case a longitudinal ventilation is chosen

The results

Consequence values for fires

On the basis of the smoke propagation simulations combined with the evacuation simulations the following damage values (model values per event) were obtained:

	5 MW		30 MW		100 MW	
	LV	TV	LV	TV	LV	TV
Tube 1 – direction Istria	2,0	0,2	4,4	4,3	29,0	5,8
Tube 2 – direction Kvarner	1,7	0,6	4,8	4,4	35,5	6,2

Table 1: Characteristic damage values for fires (fatalities per event) – Longitudinal ventilation (LV) / Transversal ventilation (TV)

The model values depicted in the tables above do not take the probabilities of the individual scenarios into account and are only valid for congested traffic situations; in normal traffic situations the value is 0 in all cases. The comparison of the values for longitudinal and transversal ventilation respectively shows the generally positive effect of smoke extraction in fires with congested traffic. In this specific case, the effect is rather low for the 5 MW and 30 MW fires, but significant in cases with bigger fire scenarios.

These values were calculated on the basis of the standard model assumptions (referring to the standard safety level without taking risk mitigation measures into account). However, in the Učka tunnel efficient additional safety measures are already in place:

- Early detection of accidents, incidents and fires by an optimised automatic video detection system and well trained and highly motivated staff in the tunnel control center as well as at the toll stations at both tunnel portals; The efficiency of this measure is documented in detail by statistical data and accident and incident reports.
- Fast and efficient tunnel closure – by means of barriers at the toll stations at both tunnel portals; as a consequence the number of vehicles entering a tunnel after an incident is limited, thus reducing the number of people possibly being effected by a fire in the tunnel.

Taking these already implemented measures into account, the model values for a 5 MW and a 30 MW fire are reduced below the respective values of the reference cases shown above, only the values for the 100 MW scenario still exceed the respective value of the transversally ventilated tunnel (see table below). However, the influence of this scenario on risk is very low - due to a very low probability.

Učka Tunnel – real conditions,			
	5 MW	30 MW	100 MW
Tube 1 – direction Istria	0,2	0,8	12,4
Tube 2 – direction Kvarner	0,4	0,8	13,3

Table 2: Characteristic damage values for fires (fatalities per event) – including effects of additional safety measures

Overall risk

Based on these specific fire damage values the overall risk of Učka Tunnel was calculated in TuRisMo. The results are compared to the two reference cases defined above (see table 3). Although the relative differences are quite small (because the fire risk is small), they are reliable – due to the relative approach, which eliminates the inevitable fuzziness and uncertainties of a risk analysis.

	Real conditions	Reference tunnel EC-Directive	Reference tunnel - RVS transversal v.
Mechanical risk	0,1009	0,1031	0,1017
Fire risk	0,0022	0,0025	0,0024
DG Risk	0,0021	0,0023	0,0034
Overall risk	0,1051	0,1079	0,1075

Table 3: Overall risk – expected value (fatalities per year)

These results can be commented as follows:

- The fire risk in the new Učka Tunnel is very low (approximately 2,0 – 2,5 %);
- Hence also the influence of all measures influencing the fire risk is very low (including ventilation, length of escape routes). This is characteristic for a tunnel with unidirectional traffic and a low congestion risk.
- With respect to the reference tunnel “EC-Directive”: the overall risk as well as the relevant partial risk of the real tunnel are well below the respective values of the reference tunnel; hence the future tunnel will be sufficiently safe with respect to the minimum safety requirements defined in the EC-directive 1004/54/EC.
- With respect to the reference tunnel “RVS – transversal ventilation”: the overall risk as well as the fire risk of the real tunnel are well below the respective values of the reference tunnel; hence the future tunnel (with a longitudinal ventilation system) will be sufficiently safe with respect to the requirements of RVS 09.02.31 in terms of selection of the ventilation system.
- The already implemented (operational) risk mitigation measures of the real tunnel are able to compensate the risk reducing effect of a transversal ventilation system in terms of fire risk; hence no further safety measure are required.

3.2. Tunnel Markovec (Slovenia)

The problem

Markovec tunnel is an approximately 2,150 km long bidirectional motorway tunnel under construction at the Adriatic coast near Koper in Slovenia; In this region a specific wind situation may occur – the so called "Bora". Bora is characterized by unsteady heavy wind with gusts with very high velocities which regularily causes problems in traffic operation. There was a concern that Bora winds may influence tunnel safety as well, resulting in a discussion to what extent Bora should be considered at the definition of the design criteria for tunnel ventilation. Therefore – in addition to a standard risk analysis – a specific scenario analysis was carried out for Markovec tunnel to investigate the influence of Bora on the risk of tunnel users

The approach

The concern was focussing on the fact, that in Bora situations much higher wind velocities can occur than normally taken as basis for ventilation design, which would lead to considerable backlayering of smoke or even spread of smoke in the wrong direction – i.e. against the direction of traffic. If this were true, this could cause harm to people in situations, when vehicles queuing behind a fire normally a protected by the ventilation system.

As basis for this investigation wind measurements of a wind measuring station in the vicinity of the Koper portal of Markovec tunnel were provided by the client. This data showed a highest recorded velocity of 15,5 m/s as absolute top value (i.e. not yet normalized on tunnel portal).

Based on the considerations outlined above a total number of 32 numerical simulations of smoke propagation was performed in order to cover a representative set of scenario developments.

The first series of simulations was based on the assumption of a 200pa wind gust for a duration of 40s on top of a basic pressure difference created by an average wind speed of approximately 4.8 m/s (15pa). This corresponds to a total velocity of approximately 18 m/s over a long period of time. This is higher than the measured velocities and the duration has more the characteristics of static wind than a short gust and can be therefore considered as very unfavourable case. Additionally a short gust of 15s has been simulated with the same velocities. For both cases 2 incident locations and 2 fire scenarios (5MW and 30 MW) have been simulated in order to assess the influence of altering longitudinal gradient and influence of moving vehicles in the early phase.

The results

As a representative example the effects of such a gust (18 m/s for 40 sec., 4,8 m/s basic wind) on smoke propagation in a 30 MW fire scenario in the self rescue phase (300 sec. after start of event) are shown in the figure below.

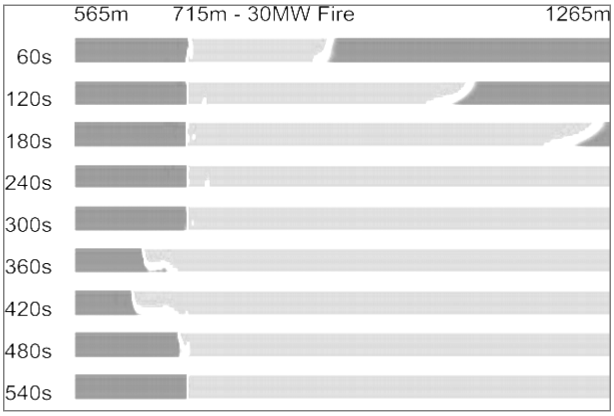

Figure 1: Smoke propagation in a 30MW fire at 715m, 40s Bora gust at 300s

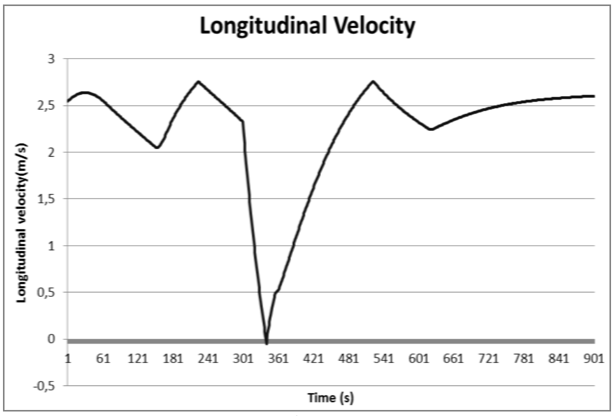

Figure 2: Evaluation of longitudinal air velocity, 30MW fire at 715m, 40s Bora gust at 300s

The gust hits the tunnel portal between 300s and 340s after the start of the fire. At this time the fire is fully developed but fire ventilation is already activated and can restore the longitudinal flow a short time after the gust has ended. The strong and long gust causes a reduction of longitudinal velocity to almost 0 m/s and which results in a temporarily concentration of smoke and flue gases at the fire location. During this phase the hot gases of the 30MW fire begin to cause some backlayering. The furthest point which is affected by smoke in the ceiling layer is about 70 m behind the fire location. However, only a very short area behind the fire location (about 20m) is affected over the entire cross section (including walking level). As soon as the longitudinal velocity reaches the target value of 2.5 m/s backlayering stops and the smoke is cleared from the upwind side of the tunnel. The time of exposure is relatively short even for persons, which are sitting still in their vehicles.

Even though the most unfavorable assumptions have been made for the investigation no relevant effects on the endangerment of people in the tunnel do result. Calculation with more realistic assumptions show no non negligible effects at all. A rough estimation of probabilities of such scenarios which may increase consequences showed that the effect in terms of a quantifiable influence on risk is negligible. Hence it can be concluded that a layout of the ventilation system according to RVS standards in this particular case would be sufficiently safe also for Bora situations.

3.3. Heidkopftunnel (Germany)

The problem

The Heidkopftunnel is a 1.7km long twin bore tunnel for unidirectional traffic in the Lower Saxony Motorway network. Since its opening in 2006 the tunnel was closed for carriers of dangerous goods (DG). Transportation of DG was routed via the highways B27 and B80 which are the assigned alternative routes.

In 2010, the new ADR tunnel regulations became effective and the Heidkopftunnel had to be classified to one of five ADR tunnel categories according to these recently established rules (category A: all dangerous goods allowed – category E: all dangerous goods forbidden). This decision should be taken on the basis of the results of a risk analysis.

In Germany a harmonised procedure for risk assessment of DG transports through is established since 2009. This methodology is outlined in the report “Procedure for the road tunnels categorisation of road tunnels according to ADR” [8]. The method consists of a multistage procedure with a rough assessment in stage 1 followed by an in-depth analysis in stage 2, if required. As on the basis at the results of stage 1 no decision could be taken, the Heidkopftunnel had to be examined in more detail with a complex, quantitative risk analysis model (stage 2a). This thorough analysis should allow a statement whether the tunnel could totally be opened for DG traffic or had to be kept closed for certain groups of DG (explosives, flammable fluids, toxic substances).

The risk analysis had to be performed for the current traffic volume (year 2010) as well as for the traffic prediction for the year 2015. Additionally a maximum traffic volume was calculated up to that the tunnel could remain open to transportation of dangerous goods.

The approach

The eight main scenarios defined in the methodology [8] represent four different types of DG in two sizes of exposure each. These types of events are:

- **Pool fire** resulting of the spill of flammable liquids

- Release of **Toxic Gases**
- Release of combustible gases (**Torch Fire**, **VCE**, **BLEVE**)
- Detonation of **Explosives**

The structure and most of the required data for the risk calculations is defined in the methodology [8]. However, in order to increase the resolution of the risk analysis the calculation of consequences was specified in 2 ways:

- Variation of **traffic** load
  Instead of computing the number of casualties for the AADT the calculation was performed for every hour of the average day curve of traffic in Heidkopftunnel. This allows to cover hours with low traffic (night) as well as peak hours with elevated risk potential. The representative numbers are then calculated as weighted average over the incident frequency (proportional to traffic volume)
- Variation of **incident location**
  Instead of computing the casualty numbers at a location in the middle of the tunnel immediately in front of an emergency exit or alternatively exactly in between two exits the incident location was moved in 10m steps along the tunnel. This means the exact location of the nearest emergency exits is taken into consideration when performing the evacuation simulation at a given incident location.

These variations of traffic volume and incident location result in a different appearance of the curves in the FN diagram. Instead of a rather small number of steps (the step size represents the frequency of a single event) the edges are smoothened out giving an almost continuous graph.

The results

The results of the risk analysis were evaluated by comparing the F/N-curves of all scenarios and also the cumulated F/N-curve (summed scenarios 1 - 8) to the reference line in the F/N diagram (see Figure 3).

The risk analysis for the current traffic volume showed that the overall risk resulting from the transportation of DG is still below the reference line which is defined as absolute risk acceptance criterion in the German methodology [8].

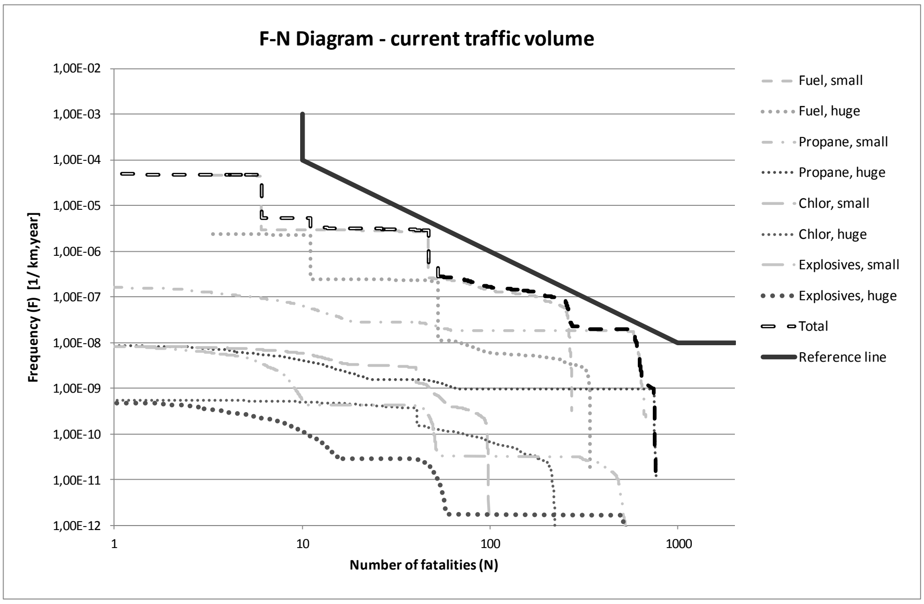

Figure 3: DG risk of Heidkopftunnel (FN curve for Traffic 2010) compared to the German reference line

However, the predicted traffic for 2015 would slightly exceed the acceptable risk level. For this reason an approximation was made in order to calculate the maximum AADT for which the tunnel still fulfils the criterion. It was found that the maximum AADT is only slightly lower than the predicted traffic for 2015.

As result of the risk analysis the tunnel could be opened to transportation of DG in January 2012 and can remain open until the calculated maximum AADT is reached.

4. CONCLUSION

The three case studies demonstrate that the use of risk analysis can provide a better basis for safety relevant decisions in tunnel design and operation, by assessing the effects on risk of the investigated alternatives in a traceable, mostly quantified manner. However the influence on risk is only one relevant parameter for such decisions, other important factors may be operational or financial aspects or influence on assisted rescue. The three examples also show, that for different problems different risk analysis methods as well as different approaches for the evaluation of the results are required. Hence, the choice of the methods should be done by considering the respective advantages / disadvantages in the context of a specific situation. The selection of the appropriate method to investigate given issues has to match the specific problem, the required depth of assessment and the available resources [2].

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