UPGRADING OF THE AUSTRIAN TUNNEL RISK MODEL TURISMO – METHODICAL AND PRACTICAL ASPECTS

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ABSTRACT

After publication of the EC Directive 2004/54/EC on minimum safety requirements for road tunnels Austria introduced a performance based approach to road tunnel safety. The Austrian Tunnel Risk Model TuRisMo was one of the first methods defining a quantitative approach to analyse and evaluate road tunnel safety. The risk model was published in the RVS guideline 09.03.11 in 2008. After more than 5 years of practical experience in applying this model an initiative was taken to upgrade the model for a wider application. The activities to improve the Austrian Tunnel Risk Model are focussing on the following aspects:

- to implement additional parameters influencing fire risk in the existing, standardized model – in particular for unidirectional tunnels
- to open the model for simulations to be able to study individual parameters for individual tunnels specifically
- to systematically evaluate the data collected on tunnel accidents and fires in Austrian motorway tunnels since 2006 in order to get a more realistic model and to improve the input data basis for the assessment of (alternative) safety measures

In 2014 a revised issue of RVS 09.03.11 (TuRisMo 2) will be published, including the modification of the standardized method as well an expansion towards a simulation-based approach for the detailed investigation of specific problems which are not covered by the standardized approach.

Keywords: Risk analysis, risk assessment, tunnel safety, Austrian Tunnel Risk Model TuRisMo

1. BACKGROUND

1.1. Experience in the application of the existing Tunnel Risk Model

In Austria the safety-relevant requirements regarding both – constructive design and equipment as well as operation of road tunnels – are defined in the Austrian Road Tunnel Safety Law (STSG) and in the tunnel guidelines (RVS 09-Tunnel) of the Austrian Society for the Research on Road-Rail-Transport (FSV). Whereas the framework for the application of risk analysis is defined in the Tunnel Safety Law, the guideline RVS 09.03.11; Tunnel – Safety – Methodology of Risk-Analysis (published in 2008) [1] is dealing with the risk based approach in detail. In this guideline a standardized risk-based approach for the assessment of accidents and fires in road tunnels is defined, including the risk analysis methodology as well as an approach for risk evaluation. This risk model (called TuRisMo) is the standard tool for the risk analysis of road tunnels in Austria.

During 5 years of practical experience in applying the Austrian Tunnel Risk Model the focus has changed; whereas in the first phase of its application the focus was on standard cases e.g. to define the danger class of a tunnel, the emphasis later shifted towards applying it as a decision making tool, thus addressing new and more complex problems.

As costs are becoming a more and more critical factor for investments in tunnel safety, risk assessment is increasingly applied to evaluate the effects of different design alternatives and / or additional risk mitigation measures on tunnel safety in a quantitative manner, to be able to optimize the cost / benefit ratio.

This may apply for the early design phase of new tunnels but is even more relevant for the upgrading of existing tunnels as in this case much more restrictions apply than for new tunnels. The topics which have to be addressed are often linked to fire risk and the performance of the ventilation system in combination with the self-rescue facilities. The existing risk model offered only limited options to deal with these topics, as for fire only limited input data for model tunnels with specific parameters was available [2]. Hence activities were initiated to improve the existing Austrian Tunnel Risk Model.

1.2. Organisation and objectives of the upgrading process

In Austria guidelines for road tunnels are elaborated by the Austrian Society for the Research on Road-Rail-Transport. On the level of this society working groups are established involving the relevant stakeholders as well as experts from University and practice. In the case of RVS 09.03.11 the Austrian Federal Road Tunnel Authority, the Federal Ministry for Transport, Innovation and Technology, the main Austrian tunnel operator ASFiNAG, the Federal Fire Brigade Organisation and experts from the University of Graz as well as from private companies were involved. ILF Consulting Engineers was commissioned to develop the core part of the model.

The development was initiated from two sides:

- The topics which came up in practice and could not be assessed so far due to limitations of the existing model; compared to other risk models – e.g. the German model (which includes a simulation module), the ability of TuRisMo to address complex problems with respect to fire and smoke propagation and evacuation were limited.
- The much more comprehensive and illustrative data now available on tunnel collisions, fires and all kinds of parameters influencing tunnel safety, which was collected systematically since 2006 (in particular by ASFiNAG) and which significantly improve the options for a quantification of many influencing factors.

Hence, the focus of the work in the working group was:

- to widen the range of application of the risk model taking the practical problems – brought in by the stakeholders – into account.
- to implement the existing data as far as possible in the new model. For parameters, where limited or no data at all was available, expert judgement should be used additionally for quantification.

2. CHANGES IN THE RISK MODEL

2.1. Basic Structure of the risk model

The Austrian Tunnel Risk Model combines a set of different methodical elements to analyse the whole tunnel system in an integrated approach.

The risk model covers the personal risk of tunnel users. The result of the risk analysis is the expected value of the societal risk of the tunnel investigated. The respective shares of risk due to mechanical effects, fires and hazardous goods are shown separately.

The method consists of two main elements: A quantitative frequency analysis and a quantitative consequence analysis.

- Frequency analysis
  An event tree analysis is applied in order to evolve a set of characteristic incident scenarios (collisions and fires) and to calculate the frequencies of these scenarios.
- Consequence analysis – collision
  To estimate the damage of collisions, the method provides default values for individual collision scenarios (depending on vehicle involvement), which were derived from statistical data of tunnel collisions.
- Consequence analysis – fire
  To estimate the damage due to fires the method provides default values for different fire scenarios, which were calculated on the basis of simulations (smoke propagation and evacuation).

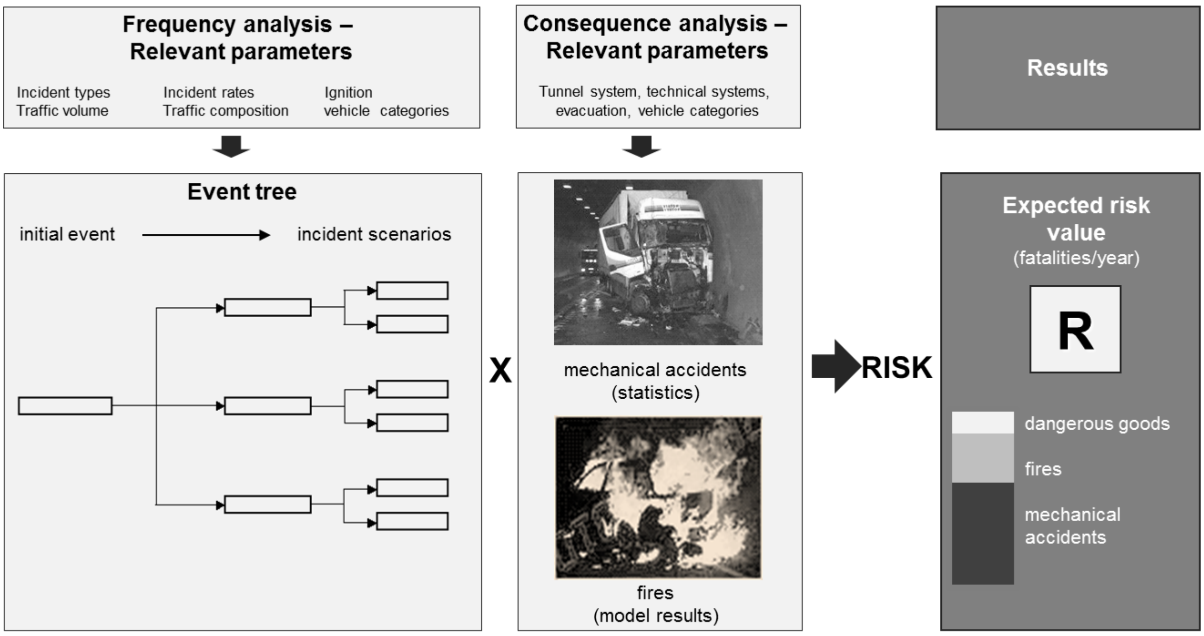

Figure 1: Structure of the Austrian Tunnel Risk Model

No changes apply to the basic structure of the risk model, as well as to the consequence analysis of collisions. However the other two methodical elements of the risk model are partly modified, in particular the consequence analysis of fires.

2.2. Structure of the event tree

In the event tree, the development of potential incidents is depicted addressing relevant parameters like traffic and vehicles. In the modification of the risk model special attention was paid to scenarios with congested traffic, because this traffic situation may have major influence on fire risk of unidirectional tunnels with longitudinal ventilation. Furthermore, these scenarios have to be addressed separately with respect to fire risk. Two types of congestion are distinguished:

- Congestion due to traffic overload
  In the new model, this type of congestion is addressed separately and introduced as individual independent branch in the event tree, because specific conditions occur with respect to airflow as well as exposure of people in case of a fire.
- Congestion as a consequence of a previous initial event (collision or break down)
  This type of congestion is relevant because it develops suddenly and can cause

collisions and fires as a consequence. It is addressed separately for two reasons: There are measures which may influence this type of collisions and – once again – specific conditions occur with respect to airflow and exposure of people in case of a fire, which differs from the other congestion type. For this type an additional branch is introduced in the event tree, which is linked to the previous initial events, collision and breakdown.

Furthermore the steps of the event tree analysis were expanded from 6 to 9, thus allowing for a clearly structured modelling of fire scenarios.

2.3. Basic incident rates and relative frequencies in the event tree

For the calculation of frequencies for the various incident types quantitative input data is needed. With respect to quantification of the event tree the general principle applies, that in the guideline default values are defined which may be modified, if significant specific data for a individual tunnel is available. The changes in the model with respect to the quantification of the event tree are based on tunnel incident data collected by ASFiNAG since 2006 (and before). Whereas relative frequencies referring to collisions (type of collision, vehicle involvement) are not changed, the basic collision rates as well as the relative frequencies related to fires were modified for the following reasons:

- There is a general decrease in the rates of collisions causing casualties in Austrian motorway tunnels [3].
- With respect to tunnel fires, a detailed analysis of data and information collected by ASFiNAG in the period 2006 – 2012 [4] covering 68 tunnel fires was executed to establish a basis for the definition of quantitative input data for the event tree.

All default values provided in the new guideline were defined after discussion in the working group, including expert judgement. Some characteristic examples are presented to illustrate the changes:

Supported by statistical tunnel incident data the basic collision rates were reduced by appr. 30% to stay abreast of the general increase in traffic safety (table 1)

Basic collision rates		
	Unidirectional	Bidirectional
RVS 09.03.11 – 2008	0,112 / 10^6 veh-km	0,077 / 10^6 veh-km
RVS 09.03.11 – 2014	0,078 / 10^6 veh-km	0,054 / 10^6 veh-km

Table 1: Basic collision rates for motorway tunnels in Austria

In the 2014 edition of the guideline – like in the original version – the basic collision rates are modified by parameters referring to traffic load and tunnel length, hence it is not admissible to conclude on the basis of the basic collision rates, that unidirectional tunnels have a higher frequency of collision with casualties than bidirectional tunnels (because the two basic rates refer to different average tunnel lengths and traffic loads).

With respect to fire, fires after a breakdown (caused by various kinds of technical failures in the vehicle or in the load) and fires as a consequence of a collision are addressed separately.

For fires after breakdown, a significantly higher frequency was found for HGVs in comparison to passenger cars. However, only a share of 38% is developing to a size which may endanger people; the majority expires by itself or is extinguished by simple means (data see table 2).

For fires initiated by a collision the relative frequency is depending on the type of collision; this type of fire typically is developing faster, hence it is assumed that 100% are reaching a critical size (data see table 2).

Vehicle category	Type of fire:	Fire after breakdown
Passenger car		0,015 / breakdown
HGV		0,01 / breakdown
Type of collision	**Type of fire:**	**Fire after collision**
Single car accident		0,012 / collision
Front – end collision		0,006 / collision
Head – on collision		0,020 / collision

Table 2: Relative frequencies of vehicle fires

Another aspect taken into account much more specifically in the new model is the development of HGV fires. Experience shows [4] that typically the fire takes some time to reach the maximum heat release rate, thus offering options for intervention. As the data allowed for a certain correlation between fire size and intervention time of fire brigade, an approach was implemented in the model which allows an assessment of the influence of the intervention time.

2.4. Consequence modelling of fire risk – modification of the standard model

In the standard risk model default values are applied for the quantification of damage in fire scenarios. These default values were calculated during the development of the risk model by applying simulations for different fire sizes to model tunnels, with variation of a predefined set of parameters (ventilation system, tunnel length, length of escape route). The range of model tunnels covered by default values corresponds more or less to practicable combinations of parameters admissible according to the Austrian guidelines, so that standard tunnels in most cases can be investigated by applying the standard approach. If parameters relevant for fire risk are not in line with requirements defined in the guideline, the standard approach cannot be applied; this applies for instance, if the capacity of a smoke extraction system is not corresponding to the values defined in the guideline. The reason is, that the simulations for the calculation of the default values were performed with these standard values and hence do not cover deviations.

Although the implementation of an approach including specific simulations as presented in chapter 2.5 was the main focus of the upgrading process, there was a consensus as well, that the standard approach should be retained and improved as well. This was done on the basis of the new detailed approach to take advantage of its increased potential.

With respect to the default values of the standard model the focus was on unidirectional tunnels with longitudinal ventilation for the following reasons:

- The predominant majority of tunnels on the Austrian (motorway) network are unidirectional tunnels; only a few bidirectional tunnels are left
- Many of the bidirectional tunnels are so specific that they cannot be covered by a standard approach anyway; to cover a rather small number of bidirectional tunnels would have required a high number of simulations and calculations for different types of model tunnels.

Hence for bidirectional tunnels the existing default values were kept, thus accepting a certain level of inconsistency in the standard model.

For the unidirectional tunnels different types of scenarios with respect to airflow and exposure of people were taken into account:

- Primary fire scenario:
  Fire in a situation with flowing traffic where the first vehicle is burning and all vehicles downstream of the vehicle on fire can leave the tunnel.
- Secondary fire scenario:
  Fire as a consequence of a collision at the end of a stopping convoy of vehicles, which is caused by a previous incident (high longitudinal airflow at the beginning; limited queue downstream of the fire, where vehicles cannot leave the tunnel).
- Tertiary fire scenario:
  Fire in the middle of a congestion, which has been caused by traffic overload; (low initial longitudinal airflow, all vehicles downstream of the vehicle on fire are trapped).

For these 3 types of scenarios default values were calculated, including a variation of the following parameters:

- Fire size: 5MW / 30MW / 100MW
- Tunnel cross section: vaulted / rectangular with 2 lanes
- Tunnel length: 0,5km – 4,0km (rectangular cross section); 0,5 - 8,0km (vaulted cross section); 0,5 - 1,0km (natural ventilation)
- Gradient: -3,0% / horizontal / +3,0%
- Escape route length: 125m – 500m

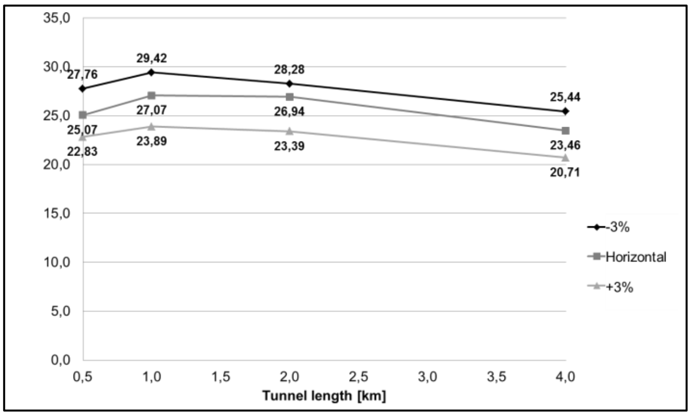

Figure 2: Model values for damage in a secondary fire scenario of a 30MW fire (example for rectangular cross section)

2.5. Consequence modelling of fire risk – the detailed model

The most relevant limitation of TuRisMo was so far, that with respect to fire risk it was limited to the default values defined in the standard model and hence to the underlying conditions. Therefore, it was often not possible to investigate tunnels with specific characteristics with respect to fire risk with the existing model. In principle, the application of simulations was also possible with the old model and in several risk assessment studies related to practical projects first steps were undertaken towards a simulation based calculation of damage values for fire scenarios. However, no specifications were available for this kind of approach.

The core element of the new detailed model integrates a 1D and a 3D CFD model and an evacuation simulation model. The application of the detailed model for consequence modelling of fire risk includes three different model fires (a 5MW fire scenario for passenger cars, a 30MW and a 100MW fire scenario for HGV's) and all relevant parameters (related to infrastructure, equipment and traffic) for the specific tunnel under investigation. When applying the model various parameter variations are performed in order to cover a broad range of different initial states as well as different possibilities of scenario evolvement.

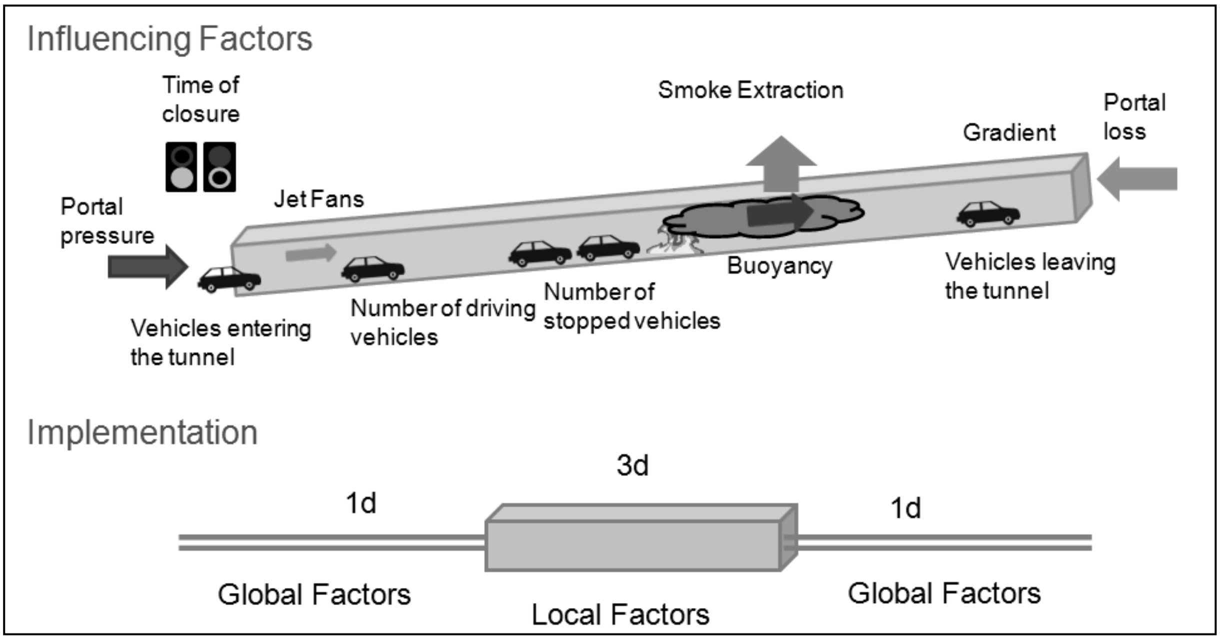

Figure 3: Relevant influencing factors in the transient 1D/3D smoke propagation model

As first step a one-dimensional simulation is carried out, which creates the boundary condition for the corresponding scenario in the 3D simulation. To model the time-dependant input parameters adequately a transient approach is applied.

All parameters influencing the longitudinal air flow conditions are covered in the 1D simulation such as:

- Movement and stoppage of vehicles in the tunnel
- Number and configuration of stopped vehicles in the tunnel
- Parameters influencing flow conditions like portal loss, drag at tunnel walls etc.
- Buoyancy depending on longitudinal inclination
- Development of effects of ventilation with respect to time

A relevant section of the tunnel around the fire site (can be longer than the actual tunnel length) is modelled in the 3D model, covering the following parameters:

- Detailed tunnel geometry (cross section, local gradient)
- Traffic configuration (local turbulence due to vehicles)
- Heat transition to tunnel walls, smoke stratification
- All local effects of ventilation

The output of the 3D modelling – the extinction coefficient (describing the visibility conditions) and the flue gas concentrations (describing the tenability conditions) at a height of 1,6m – is transferred directly into the egress model influencing the movements of escaping people in the tunnel. The visibility influences walking speed, whereas the accumulated flue gas concentrations may cause immobility, if defined thresholds are exceeded [5] [6].

In a next step the fire site is shifted systematically along the tunnel axis, in order to cover all emergency exit configurations relevant for the scenario under investigation. The result can be described as zones with different survival probabilities, which in the final step are superposed with those areas, where vehicles are present (close to the fire site as well as in all tunnel zones located next to a location, where the traffic can be stopped). The damage values of the individual scenarios multiplied by the respective probabilities are finally summarized to calculate the statistically expected damage value for a basic fire scenario. This procedure is applied for all scenarios investigated.

Furthermore, the variation of the following parameters shall be covered to some extent, depending on the specific situation of the tunnel under investigation:

- Unidirectional tunnel: separate investigation of each tube
- Traffic: three different traffic scenarios, representing low, average and high traffic situations, thus covering varying exposure as well as well as different flow conditions; in case of bidirectional tunnels the symmetry of the traffic is covered by three sub scenarios for each basic traffic case; a method is defined how to deduce these representative traffic scenarios from statistical traffic data
- Fire location: depending on gradient, changes in cross section and tunnel length 2-5 fire locations should be investigated
- Meteorological influence: if relevant, representative portal pressure differences shall be taken into account

3. CHANGES IN THE APPLICATION OF THE MODEL

3.1. Risk evaluation

For the final step of the risk assessment process, the evaluation of the results of the risk analysis, a twofold approach is applied:

- The absolute risk level is taken as basis for assigning the tunnel to one (out of four) danger classes. In the Austrian Tunnelling Guidelines a categorisation system consisting of 4 danger classes is applied to determine the levels of performance for parts of the civil design as well as the equipment of the tunnel.
- Risk evaluation by means of a reference tunnel; this reference tunnel is defined as a characteristic tunnel which assures, that all minimum safety requirements subject to the Austrian Tunnel Safety Law (which are applicable to the tunnel under investigation) are fulfilled. For this reference tunnel a reference risk profile is determined, applying the same risk analysis method (and the same parameters except those which are different in the reference case), which hence represents an acceptable safety level.

In the updated guideline this approach was not changed, however, the requirements for the reference tunnel are specified much more in detail in order to overcome ambiguities. The definitions for the reference tunnel include traffic parameters, some aspects of the tunnel system and geometry as well as requirements for the ventilation system.

One specific aspect in Austria is, that the technical requirements according to the RVS-guidelines are stricter and more specific than the minimum safety requirements according to the Austrian Tunnel Safety Law. Hence the risk level of a tunnel in line with the guidelines is normally below the reference case. However traffic parameters or other special characteristics may cause additional risks which have to be compensated by additional safety measures. For instance a slip road belonging to an interchange connected to a tunnel is not considered in the reference system hence the additional risk has to be compensated.

Temporary phases with bidirectional traffic are addresses separately: The risk of such situations has to be assessed, but the requirements with respect to the reference tunnel are less strict.

Another new element in risk evaluation is the inclusion of activities of the rescue services. In addition to the parameters already involved in the risk model, specific positive or negative conditions can be included in the final evaluation of the results in a qualitative way. In this context, an intervention time of the fire brigade of 15 minutes is defined as characteristic reference value.

3.2. Risk mitigation measures

The updated model, in particular the detailed version, is enhancing the options for a quantitative evaluation of the effects of risk mitigation measures a lot, in particular with respect to fire risks; however, with respect to measures influencing the frequency of tunnel collisions, a certain need for further research is remaining.

For the selection of the most suitable risk mitigation measures two principles are defined:

- The measures should specifically address topics, where specific problems were identified in the risk analysis.
- The ALARP (As Low As Reasonably Practicably) principle is established thus introducing a cost-effectiveness approach for the selection of measures

4. EXPANSION OF THE RANGE OF APPLICATION OF THE RISK MODEL

It was a key objective of the upgrading process from the very beginning to widen the range of application of TuRisMo to be able to address various kinds of specific problems as well as measures to mitigate these problems in a quantitative manner. In particular the owners and operators of tunnels are interested to display investments into tunnel safety in a quantitative way in the risk balance, including the option to bring in innovative solutions. Hence, a short summary of typical questions is presented which can be addressed on the basis of the enhanced model.

Tunnel geometry and tunnel system:

- In the detailed model, the individual detailed structure of a tunnel is taken as a basis; hence all characteristics and irregularities of an individual structure are implemented in the study, such as varying emergency exit distances (real configurations), changing tunnel cross sections, changing gradients etc.
- The effect of a continuous emergency lane can be assessed as well as the distance of lay-byes.

Traffic and operational aspects:

- In the detailed model, a transient approach is applied. Hence the influence of vehicle movements and all kinds of influencing measures can be addressed, such as a speed regulation or location and type of facilities for stopping the traffic in front of and / or inside the tunnel.
- Specific traffic situations and special traffic characteristics can be assessed.
- Time delays in detection as well as the reaction of relevant safety systems (like ventilation) can be taken into account.

Fire and smoke control:

- Combined ventilation systems can be studied as well as all kinds of unconventional ventilation solutions (e.g. local extraction or injection).
- The specific capacity of a ventilation system (including local anomalies like varying extraction capacities or leakages) as well as the operational strategy (e.g. operation mode over time, modification of airflow velocities) can be assessed.
- As secondary fire scenarios are also included, the effects of a longitudinal ventilation system in a long tunnel can be studied in detail.
- Specific meteorological situations (like strong winds or barometric pressure differences at tunnel portals) can be studied.

- The effects of fixed firefighting systems can be implemented in the model; however, this requires specific data form real fire tests and a modification of the 3D-model.
- Early intervention for firefighting can be assessed.

5. CONCLUSIONS

After more than 5 years of practical experience the Austrian tunnel risk model TuRisMo was upgraded by implementing new data and additional parameters. In addition to the standard model a new detailed model with a simulation based approach was developed, thus increasing in particular its capabilities for a detailed investigation of factors influencing fire risk.

The standard approach is easily and quickly applicable by implementing default values in an event tree based on a spread sheet approach whereas for the application of the detailed model a complex simulation environment has to be set up, which requires much higher resources and specific knowledge and experience of the user.

TuRisMo 2 is well suited to perform all kinds of risk-based studies such as

- Select the best design alternative or combination of risk mitigation measures available to minimize risk.
- Identify the most cost-efficient solution to fulfil the minimum safety requirements
- Quantify the effects on risk of specific shortcomings in existing tunnels (e.g. in the ventilation system).
- Quantify the effects on risk of potential compensation measures and identify the most cost-efficient combination of compensation measures.

TuRisMo 2 will be published in 2014 in a revised issue of RVS 09.03.11, including the modification of the standard method as well as a guidance to the new detailed approach.

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